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Controlling the Spatial Coherence of Lasers for Imaging and Sensing

Douglas Stone
YALE UNIV NEW HAVEN CT

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14. ABSTRACT
The goals of this project were to build on our earlier work demonstrating an on-chip semiconductor laser source which generated emission with low spatial coherence, providing a uniquely efficient illumination source for speckle-free imaging and other optical tasks. In our first successful design, the laser was based on a D-cavity shape with chaotic ray dynamics, which enhanced the number of lasing modes. Low spatial coherence was achieved, however the D Laser did not provide a directional output beam, making it an inefficient source. In the current project we proposed to design new laser cavities with low spatial coherence and directional emission, and to also demonstrate the ability to tune in situ the number of lasing modes and hence the degree of spatial coherence of the output. Tunable coherence is important for achieving optimal illumination for applications such as holography. We continued to study chaotic cavity lasers but in the past year also proposed a new onchip cavity design with stable axial lasing modes promoting directional emission, and performed ab initio simulations to find the geometry (cavity stability parameter) that maximized the number of lasing modes.

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Controlling the Spatial Coherence of Lasers for Imaging and Sensing
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A. Douglas Stone and Hui Cao
Department of Applied Physics and of Physics
Yale University, New Haven, CT 06520

To: Dr. William P. Roach, Program Officer, Laser and Optical Physics

1. Background, goals and evolution of the project

Prior to this project the PI and Co-I had established themselves as pioneers in the field of novel microcavity lasers and specifically on chaotic cavity [Nöckel1997, Cao2015] and random [Cao1999, Tureci2008] lasers. They have worked extensively and often in collaboration on the fabrication, experimental study, theoretical description and practical applications of random and chaotic-cavity lasers. Between 2011 and 2015 the co-I and PI demonstrated that such lasers are promising illumination sources for speckle free imaging, microscopy and other applications [Redding2011, Redding2012, Redding2015]. The mechanism for speckle-free illumination was the extreme multimode character of such light sources, which leads to a high degree of spatial incoherence in the emitted field, while retaining the brightness associated with lasing (as compared to e.g. LEDs), and the speed of full field imaging (without needing to employ a diffuser). Specifically in 2015 [Redding2015] they designed a D-shaped on-chip chaotic cavity semiconductor laser which lased on ~ 500 modes and showed very low speckle contrast in imaging tests. However an inherent design property of this laser was non-directional emission, making it an inefficient and unwieldy source for applications. Solving this problem was one major motivation and goal of the project. In addition, the co-I has worked extensively on lasers with tunable spatial coherence, the best-known example being the degenerate cavity laser [Knitter2016]. Tunable spatial coherence allows toggling between different sensing modalities such as imaging and tracking. In the project we also proposed to study implementing tunable spatial coherence in on-chip sources via selective pumping of the cavity. The PI of the project has pioneered Steady-state ab initio laser theory (SALT) [Tureci2008, Ge2010, Cerjan2016] which is specifically designed to treat multimode lasing in complex cavities of the type we had and would study. This was the basic theoretical design tool employed in the project.

Here is the summary of our stated goals for the project at its outset:

- Study theoretically the trade-off between directional emission and spatial incoherence for the relevant laser designs.
- Design, fabricate and test different laser cavities to determine the maximum power and directional emission intensity obtainable while maintaining low spatial coherence.
- Study theoretically (within SALT) and experimentally in semiconductor microcavity lasers the use of the spatial pump profile to control the number of modes, and hence the spatial coherence of the emission.

- Develop a monolithic on-chip laser system with tunable spatial coherence so as to enable multiple functionalities for imaging and tracking with the same laser.

We have substantially met all of the stated goals through our research under this project. In addition we have pioneered a new on-chip laser design which was not envisioned in the original proposal.

Around the time the project was funded, the co-I, through her study of degenerate cavity lasers with tunable spatial coherence, conceived of an on-chip stable cavity laser design which would have intrinsically directional emission, due to its more conventional geometry. The hypothesis was that this design might be sufficiently spatially incoherent to achieve speckle-free imaging when *all* possible modes are lasing, and also might be tunable through spatially selective pumping so as to operate in a spatially coherent modality. A standard degenerate cavity laser is a table-top device, in the simplest case based on two spherical mirrors, with spacing and curvature tuned to the confocal point, at which all transverse modes are degenerate with the fundamental axial mode *and* have similar Q-factors, making it possible to lase on all modes simultaneously. Moreover, single mode lasing can be achieved by means of an intracavity aperture. The proposed on-chip stable cavity would have dielectric mirrors with angle and polarization dependent reflectivity, making it unclear what geometry would maximize the number of lasing modes. Furthermore it would not be tunable in situ with an aperture, but might be with spatially-selective pumping. As the project evolved we focused on this design to achieve the project goals while continuing our study of the physics of chaotic cavity lasers to understand their essential physics better. We will first describe the results obtained for the new mirror-based on-chip design. We term this laser an on-chip stable dielectric cavity laser (OSDC laser) for reasons to be explained below.

2. OSDC laser with low spatially coherence and directional emission

As discussed above, we designed and fabricated an on-chip dielectric cavity laser to mimic a conventional mirror-based macro-cavity using a dielectric structure with a GaAs/AlGaAs active layer bounded by two curved end-facets with constant radius of curvature, R_c, and axial separation, L, pumped electrically by an appropriately shaped contact (see schematic, Fig. 1(f), and SEM image, 1(g), below) [Kim2019]. The cavity was fabricated on a GaAs quantum well wafer by photolithography and reactive ion etching. The SEM images in Fig. 1(g) reveal the high quality of the etched facet. Prior to fabrication we performed passive cavity simulations, and then SALT simulations, of the active cavity to determine the optimal geometry for highly multimode lasing [Cerjan2016, Kim2019]. In our design study we varied the cavity stability parameter $g = 1 - L/R_c$ [Fig. 1(a)], with $g = 0$ corresponding to confocal (degenerate cavity) and $g = -1$ to the concentric cavity. Somewhat surprisingly, we found that the value of g which optimized the number of lasing modes was not near the conventional degeneracy point, but rather near-concentric ($g = -0.74$) [Fig. 1(e)]. This optimal value results from a subtle interplay of the reduced mirror reflectivity for the favored TE lasing modes at non-normal incidence (typical of a confocal cavity), and the higher diffraction loss of the concentric cavity. When optimized for the maximum number of lasing modes this favors a g value in between the two but closer to concentric. Figs. 1(b-c) show examples of high-order transverse modes for different values of g. Note that the simulations showed that the number of lasing modes is very close to the number of passive cavity modes in the near-concentric regime, where the modes are more spatially spread out, but is significantly below that number closer to the confocal point, where modes overlap more in space and compete for gain.

The simulations could only be performed for cavity sizes up to L=20 μm, and predicted about25 lasing modes at that scale, whereas the experimental lasers we fabricated were intended to lase in ~ 500-1000 modes in order to suppress the speckle contrast below 3%, hence the fabricated lasers had L in the range 400-800 μm [Fig 1(g)], far beyond the scale that can be simulated even using the highly efficient SPA-SALT approach we employed [Cerjan2016, Kim2019]. The experimental results below [Fig. 2(g)] show that the near-concentric design does indeed perform substantially better than either the confocal or concentric. These results provides a strong validation of the SALT approach we use for laser design and mode control.

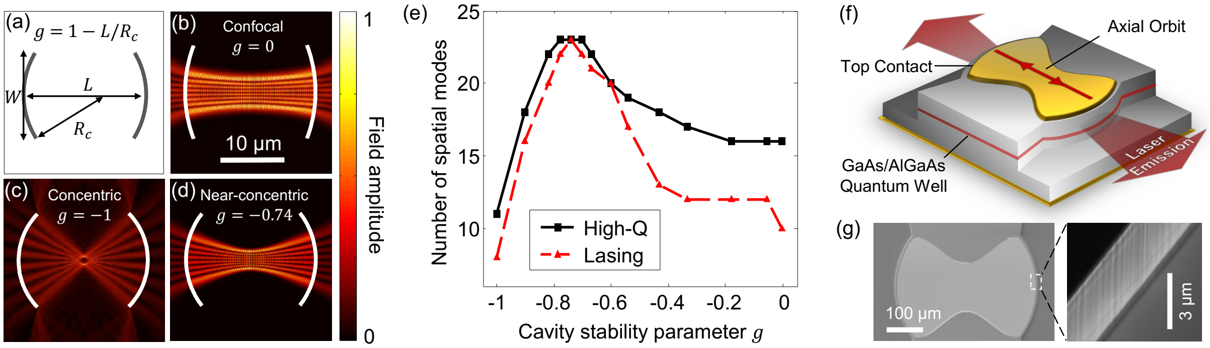

Fig. 1. (a) The geometry of the stable cavity configuration, defined by a cavity stability parameter $g = 1 - L/R_c$. (b) Mode profile of a high-order transverse mode in confocal (g = 0), (c) concentric (g = -1), and (d) near-concentric (g = -0.74) cavities. (e) The number of high-Q axial modes (black squares) and the number of lasing modes (red triangles) at the pumping level of two times of the lasing threshold for different cavity geometries. The number of spatial modes is maximized in the near-concentric regime in which the emission is directional as well. (f) Schematic of the stable cavity semiconductor laser. (g) SEM images of a fabricated cavity with the optimized geometry (g = -0.74). The etched facet is vertical and smooth.

Lasing characteristics of the OSDC lasers are presented in Fig. 2. The lasers are electrically pumped with 2 μs-long current pulses at room temperature. For the optimized near-concentric cavity, the emission is indeed directional with a half width at half maximum of 35°, as shown in Fig. 2(a). Measuring the spatial coherence of the laser emission requires introducing scattering to generate speckle. This was done using a diffuser and the far-field speckle pattern was recorded. We quantified the number of spatial modes as $M = 1/C^2$, where C is the speckle intensity contrast. As shown in Fig. 2(b), a near-concentric cavity supports a larger number of spatial modes compared to concentric and confocal cavities, leading to small values of C over a very short integration time. The speed of speckle suppression is crucial for imaging applications. This is one major motivation for having an intrinsically spatially incoherent source (instead of using an external rotating diffuser).

For multimode lasers, distinct frequencies of different lasing modes can accelerate the decoherence process. Degenerate cavity lasers [Chriki2018] and random lasers [Redding2012] feature decoherence times on the order of 10-100 ns. To investigate the applicability of the OSDC laser to ultrafast speckle-free imaging, we determined how fast the decoherence of the laser emission occurs [Tureci2008].

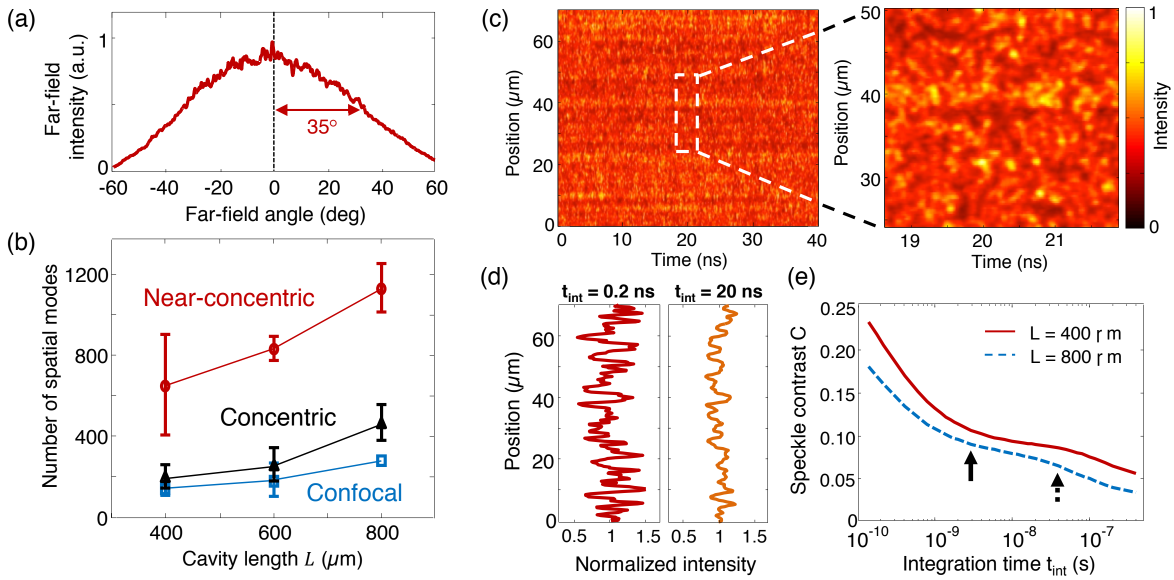

Fig. 2. (a) Far-field intensity pattern of laser emission from a near-concentric (g = -0.74) cavity of length L = 400 μm. (b) The number of transverse lasing modes from near-concentric (g = -0.74), concentric (g = -1), and confocal (g = 0) cavities with different cavity length L. (c) The spatio-temporal evolution of the far-field speckle intensity pattern from the near-concentric laser in (a). The magnified view reveals fast temporal evolution of the speckle pattern. (d) Time-integrated speckle patterns for integration times 0.2 ns and 20 ns, with speckle contrast of C = 0.21 and 0.098, respectively. (e) Dependence of speckle contrast on integration time, exhibiting two kinks at the integration times of a few nanoseconds (solid arrow) and several tens of nanoseconds (dashed arrow).

Using a streak camera, we measured the spatio-temporal evolution of the far-field speckle pattern. Fig. 2(c) reveals rapid variation of speckle pattern in time. As a result, the contrast is reduced significantly for an integration time t_{int} as short as 20 ns, shown in Fig. 2(d). The speckle contrast as a function of the integration time t_{int} was investigated and plotted in Fig. 2(e). After a rapid drop, the speckle contrast starts to saturate, exhibiting a kink at an integration time of a few nanoseconds. The ultrashort integration time needed for contrast reduction originates from the larger spacing of the lasing modes in the small OSDC cavity (compared to degenerate cavity lasers). A second kink at a few tens of nanoseconds is attributed to the thermally-induced variation in lasing modes. This improved speed of speckle suppression represents a significant improvement over prior work.

3. Laser coherence control by adaptive pumping

For imaging and sensing applications, laser illumination sources with an intermediate degree of spatial coherence are often needed. A good example is digital holography: the light that illuminates a hologram must be sufficiently spatially coherent to produce a holographic image but low enough to avoid speckle noise. Typically speckle noise is a serious issue for holographic imaging, and different solutions have been developed to de-speckle, including "spectral compounding", using lasers of different frequencies, numerical denoising filter techniques, and others. However, the most direct and efficient way of removing speckle is to use a laser source with an optimal degree of coherence for the specific imaging or sensing task [Cao2019]. This motivated one of the project goals, that is to achieve tunable coherence for the OSDC laser via spatially selective pumping.

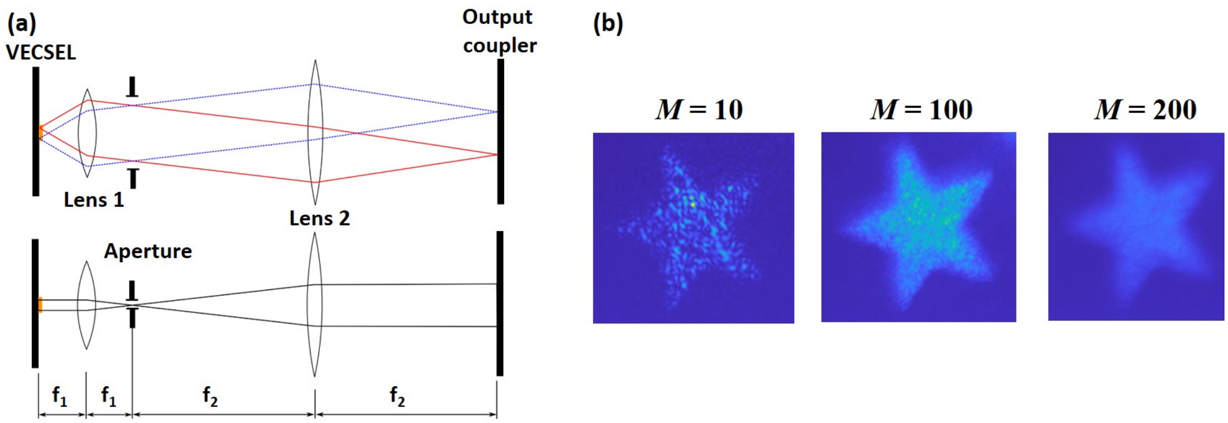

Fig. 3: (a, b) Schematic of a degenerate cavity laser with VECSEL, high numerical-aperture lens, an aperture, reimaging lens and output coupler (OC) mirror. In multimode operation (a) locations on the VECSEL are imaged onto the OC and vice-versa, yielding a large number of independent spatial modes (low spatial coherence). In few-mode operation (b) an aperture in the mutual focal plane of lens 1 and lens 2, yielding plane-wave emission through the OC (high spatial coherence). (c) The holographic image of meta-surface hologram when illuminated by the laser emission from the degeneravity cavity with varying number *M* of transverse lasing modes. As *M* increases, the spatial coherence decreases, and the speckle noise is suppressed.

Above we show a proof of concept experiment performed by the co-I in a previous project using a table top VECSEL-based (vertical external cavity surface emitting laser), degenerate cavity laser, see Fig. 3(a, b) [13]. To find the optimal degree of spatial coherence for holographic imaging, we continuously tune the number of transverse lasing modes in the degenerate cavity. The output laser beam illuminates a meta-surface hologram and the resulting holographic images are shown in Fig. 3(c). When the number of transverse lasing modes *M* is small (M=10), the laser light has high spatial coherence and the speckle noise in the holographic image is substantial. As *M* increases, the spatial coherence of laser light decreases and the speckle noise becomes weaker. As *M* increases further the speckle noise becomes negligible, but the hologram itself becomes fainter. These results demonstrate that an optimal degree of sptial coherence exists for speckle-free holographic imaging.

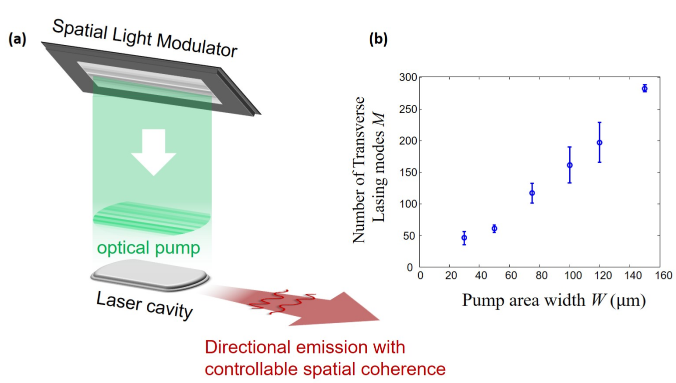

Fig. 4: (a) Schmatic of spatial modulation of the intensity of optical pumping across a near-concentric cavity with a spatial light modulator to vary the number of transverse lasing modes. (b) Experimentally measured number of transverse lasing modes *M* as a function of the pump area width.

Consistent with the project goals, we attempted to achieve similar results to the table-top VECSEL setup in a monolithic on-chip source, the OSDC laser. Here we cannot use intracavity elements such as apertures and instead we tune the spatial coherence by adaptive, spatially selective pumping. As shown schematically in Fig. 4(a, b), we spatially modulate the pump intensity distribution to adjust the number of transverse lasing modes M in the optimized, near-concentric OSDC laser. With the total pump power being fixed, a gradual widening of the pump area increases M by a factor of 6, as shown in Fig. 4(b). We are able to obtain the number of transverse lasing modes that provides speckle-free holographic image in Fig. 3(b). Further research should be oriented towards determining if adaptive pumping of the OSDC can achieve few-mode very high spatial coherence, which may be useful in other imaging/tracking applications.

Through our development of the OSDC laser we were able to meet the major goals of the project as stated in our original grant proposal, however with a different design than we had anticipated, since our first design for a spatially incoherent on-chip semiconductor source was the D-shaped chaotic cavity laser. Prior to the current work it had been shown that random and chaotic lasers could be induced to emit with directionality, either through shape design (for chaotic cavities) or through adaptive pumping, and we had intended to explore this question in great detail. In the end we found that the OSDC cavity met our goals with a more straightforward geometry. However we did devote significant effort in the project to explore the fundamental laser physics of chaotic cavities and to clarify the open question as whether chaotic cavity lasers are highly multimode or single-mode.

4. Origin of highly multimode lasing in chaotic laser cavities

Dielectric cavity lasers fabricated with boundary shapes which generate fully chaotic or partially chaotic ray dynamics have been studied for over twenty years, since the pioneering work of the PI [Nöckel1997, Cao2015]. The original motivation for such shapes was to achieve directional emission while keeping relatively high-Q modes in a few micron scale cavity.

There were no reliable methods to calculate the lasing mode spectrum of such lasers in a predictive manner until the development SALT theory between 2006 and 2010 [Ge2010, Cerjan2016], which treats quantitatively the spatial hole-burning and mode competition in such complex cavities with an active medium. Much more recently, as noted above, due to the work of co-I and PI, the potential applications of such cavities to speckle-free imaging was appreciated and then demonstrated using a D-shaped chaotic cavity semiconductor lasers with very small speckle contrast due to extreme multimode lasing [Redding2015].

Just before the beginning of this project questions were raised as to whether chaotic cavity lasers should *actually* lase in stable single-mode operation, at least in steady-state. The lasers we had studied, which were demonstrably highly multimode, were operating in a pulsed mode, whereas fairly similar semiconductor lasers, based on a stadium shaped microcavity, were found in work in Japan to be single-mode in CW operation, at least high above threshold [Sunada2016]. Because we had studied only D-shaped cavities, we decided to study stadium-shaped and elliptical cavities, based on improved surface processing fabrication methods.Thus we could test the effect of several factors on the lasing spectrum: 1) whether the lasing spectrum differed between two fully chaotic shaped cavities. 2) whether the lasing spectrum differed between a regular (elliptical) cavity or a chaotic cavity with similar aspect ratio and area. 3) whether improved surface quality would lead to single or few mode operation, in contrast to our earlier devices. Also, we studied carefully the lasing spectrum of our devices as a function of the length of the pump pulse, over a range of 2-500 μs, to see if there was some evidence of a reduction of the number of modes as a function of the length of the pump pulse (the design of our lasers did not allow CW operation due to thermal effects). We have published a detailed study of these questions [Cerjan2019] and will just summarize the highlights here:

- Our experiments reproduced the results of multimode lasing for both of the chaotic cavity lasers, the D and the stadium. The only qualitative changes in the performance due to the improved surface quality (see Fig. 5) was a reduction of the threshold for the onset of lasing.
- We did not find a systematic decrease in the number of lasing modes active at the same time with the length of the pulse, although we were able to resolve the large fluctuations of the spectrum during longer pulses with various modes turning on and off over the course of the pulse.
- For few micron size cavities, SALT theory found more lasing modes in the D-cavity than for the stadium, which has high-Q "scarred" modes which clamped the gain. However, this difference disappeared as the cavity size scale exceeded 20 μm, well below the size of the experimental lasers. At larger scale both chaotic shapes had very similar lasing spectra.
- As expected, an elliptical cavity with the same aspect ratio as a stadium cavity showed fewer lasing modes at larger sizes due to the presence of high-Q whispering gallery modes.
- The SALT calculations showed that spatial hole-burning and gain competion alone are never sufficient to induce single-mode lasing in the chaotic cavities studied. SALT assumes steady-state, continuous-wave operation. The experiments of ref. [Sunada2016] could not be explained within SALT theory, which would imply that effects beyond gain saturation are involved, such as synchronization. In this context, it is interesting that SALT was able to predict accurately critical properties of the multimode spectrum of the OSDC laser discussed above.

Representative devices and spectral data are shown in Fig. 5(a-f) below.

In a following study [Bittner2019] we have looked at the internal intensity patterns of the two chaotic cavities and found a rather dramatic violation of ergodicity which we explain in terms of finite Q-factors of the modes (or non-random ray escape from an open resonator in a semiclassical model). Specifically, rays confined by total internal reflection at the circular boundary sections of both the D-cavity and the stadium create a pseudo-caustic within the resonators within which the field intensity is negligible, in contrast to the ergodic modes of a closed cavity. This effect is only well developed for the high-Q modes relevant to lasing, and for these modes it is captured qualititatively and quantitatively by ray-tracing and ray escape models. As a consequence the emission from the side walls of the resonators is peaked at certain points and not uniform. This effect is seen in experiments in good agreement with ray models and passive cavity mode calculations (Fig. 6).

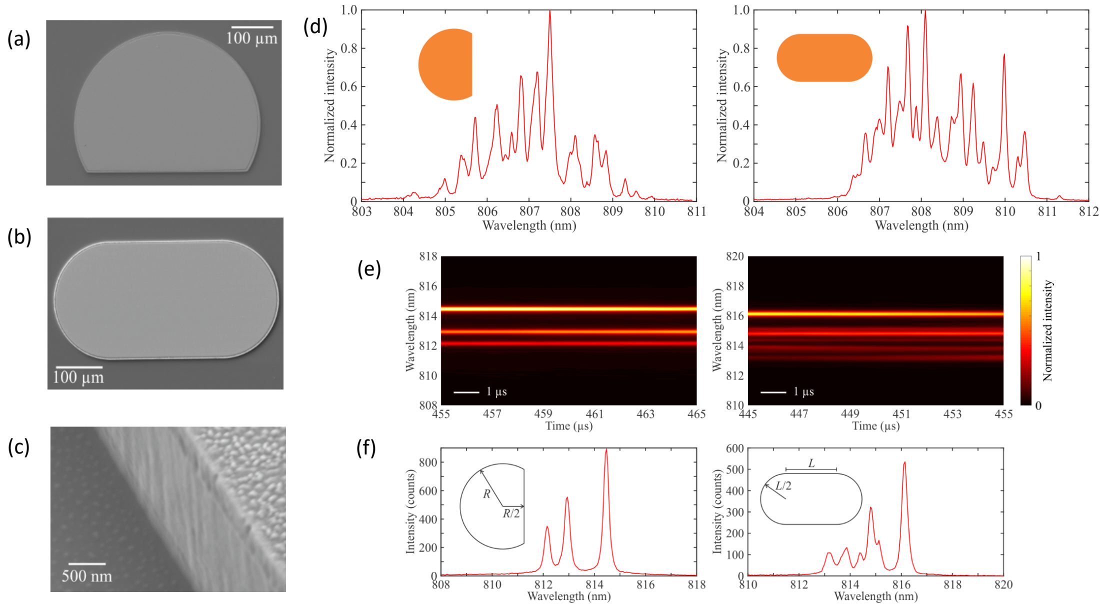

Fig. 5: (a, b) SEM image of D-shaped and Stadium cavity micro-lasers. (c) Micron scale SEM image of a sidewall, showing the very good surface quality. (d) Lasing spectra of D cavity laser (left) and Stadium cavity laser (right) integrated over a 2 µs-long pump pulse, showing highly multimode lasing. (e) Spectrochronograms of D-cavity (left) and stadium (right) near the end of a 500 µs-long pump pulse show that the lasing spectra reach a quasi-steady state, showing not variation on a time scale of 10 µs. The total number of peaks is lower than in (d), but each peak is assumed to consist of several lasing modes. (f) Plot of the short-time spectra for D-cavity and stadium integrated over 1 µs near the end of a 500 µs-long pulse. No qualitative differences are observed between the spectra of the two shapes. Over longer time scales, lasing peaks fade out and new ones appear leading the complex integrated spectra show in (d). No indication of an evolution towards single-mode lasing was found for pump pulses as long as 500 µs.

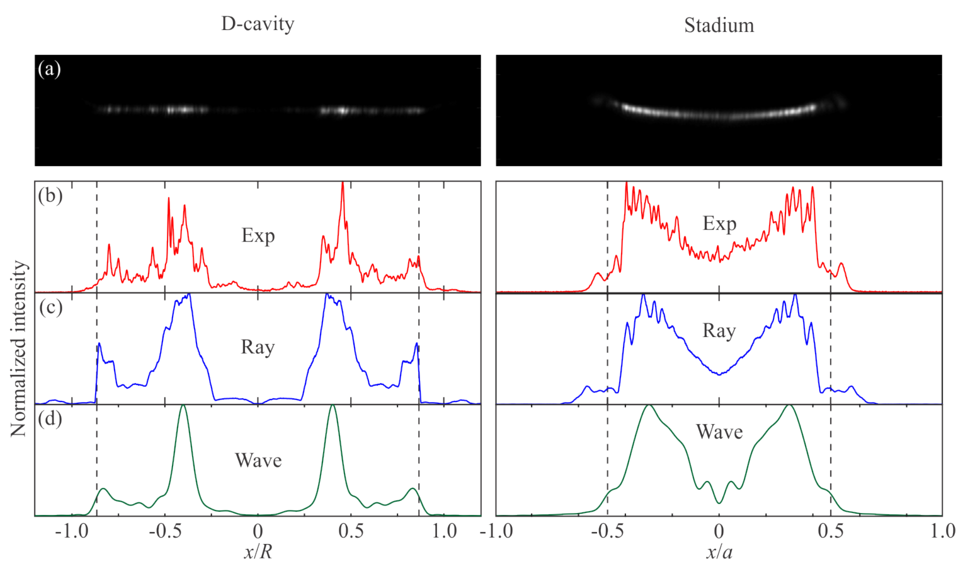

Fig. 6: Emission intensity distributions on the sidewalls of a D-cavity with R = 100 µm (left column) and a stadium cavity with a = 119 µm (right column). (a) Images of the lasing emission for a pump current of 500 mA (well above the lasing threshold) measured with a CCD camera. An objective with numerical aperture NA = 0.4 is used for imaging. The image planes are indicated as blue dashed lines in Figs. 5(a, f). (b) Measured intensity profiles obtained by vertically integrating the CCD images in (a). (c) Ray simulation and (d) wave simulation of the emission intensity distributions. The wave simulation result is the sum of many high-Q modes as in Fig. 5(d). The vertical dashed lines indicate where the circular boundaries meet the straight boundaries of the microcavities.

5. Stabilization of temporal fluctuations in chaotic cavity lasers

Another aspect of our study of chaotic-cavity semiconductor lasers, which was partially supported by this grant, was the effect of chaotic geometry on the temporal dynamics of semiconductor lasers. Conventional broad-area high-power semiconductor lasers are known to suffer from spatio-temporal instabilities and filamentation, which hamper their applications. Prior to our study little was known about the effect of the cavity shape on the laser dynamics, and specifically the effect of a chaotic cavity shape, which results in speckle-like spatial mode patterns with no extended smooth wavefronts.

We measured the spatio-temporal dynamics of lasing emission from a standard edge-emitting broad-area semiconductor Fabry-Perot (FP) laser and a D-cavity laser using a streak camera [Bittner2018]. Results are shown in Figs. 7(a, b), where we compare the experimentally measured intensity distribution at the output facet of an FP and D-cavity claser as a function of time. The FP laser shows self-pulsations on a GHz frequency scale and transverse movement of high-intensity spots, so-called filaments. In contrast, the lasing emission from a D-shaped microdisk is much more stable. The intensity pattern displays only very slow variations on a time scale of 10-100 ns. Similar results were obtained for stadium cavities. Our findings indicated that the laser instabilities are strongly suppressed in the chaotic microcavities, due to the reduction of nonlinear interactions of lasing modes. The full results of our study appeared [Bittner2018] and were reported in an earlier progress report. We include this brief summary here for completeness.

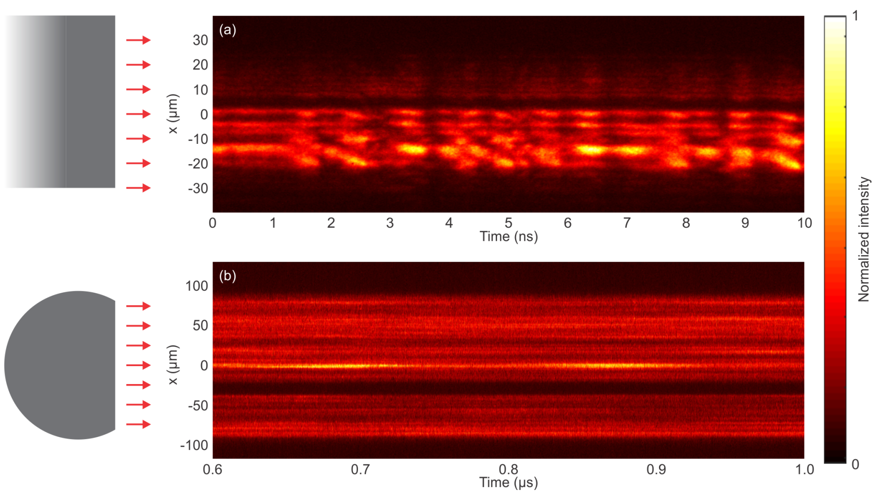

Figure 7: Spatio-temporal dynamics of lasing emission, measured at the output facet of a GaAs Fabry-Perot broad-area laser (a), showing fast self-pulsation, and at the straight sidewall of a D-shaped micordisk (b), exhibiting much slower temporal variation of the lasing emission.

6. Summary

We have achieved the main goals of the project by demonstrating an on-chip laser source with low spatial coherence and directional emission, suitable for speckle-free imaging and other applications in which speckle noise is a limiting factor. Specifically, we have designed a new type of dielectric cavity semiconductor laser, an on-chip stable dielectric cavity laser (OSDC), with a geometry similar to that of a table-top curved mirror laser, but on the 500 μm scale. As predicted by design studies based on SALT theory, the largest number of lasing modes and the smallest speckle contrast is attained for a near-concentric mirror spacing, and not the confocal (degenerate cavity) geometry. This is due to properties of the dielectric mirrors and the gain medium and can be understood from qualitative considerations noted above. We also showed that we could tune the number of lasing modes by pumping the OSDC laser in a spatially selective manner. Such coherence tuning is important for optimal production of holographic images. In addition we explored further the physics of on-chip chaotic cavity semiconductor lasers, which also exhibit low spatial coherence. We verified that highly multimode lasing was achieved for two different chaotic cavity designs, the D-cavity and the stadium, with qualitatively similar characteristics, and that this persisted for long pump pulses, suggesting that it is a steady-state phenomenon. We were able to understand non-ergodic property of the high-Q modes using ray optical models. Future work could explore improving the thermal management in these on-chip lasers so as to allow continuous wave operation.

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2. S. Bittner, S. Knitter, S. F. Liew, H. Cao, "Random laser dynamics with temporally modulated pump," *Phys. Rev. A* **99**, 013812 (2019)

3. H. Cao, R. Chriki, S. Bittner, A. A. Friesem, N. Davidson, "Complex lasers with controllable coherence," *Nature Reviews Physics* 1, 156 (2019).

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