Response to Reviewer's comments

We are thankful to the Reviewer for the advanced comments and suggestions provided below. We appreciate the great amount of time invested in giving constructive criticism of our manuscript. We provided our responses on a point-by-point basis as previously.

We attach the marked up manuscript at the end of this document.

On behalf of all authors,
dr. Darius Gailevicius

- Comment by the Reviewer:

Comments and Suggestions for Authors
You have nice results describing the change in the laser brightness when a structured light is used for pumping a disc laser. The experimental data for sure should be presented in good scientific journal dedicated to quantum optics or photonics.

However there are weak points of your paper:

1. The introduction is the weakest part of the pater. The information you provides is a mess. It is not clear what ia general feature of VECSEL for instance and what ia a specific feature observed in particular experiments. It demonstrates authors small knowledge on the laser architecture and the physical mechanisms behind the beam quality. There is lack of the precision require in science. I would advise to concentrate your introduction on the optically pumped disc lasers or even microchips laser. The broad approach you took makes the introduction miss leading the readers. What you write is often not precise or simply untrue. This has to be changed. In your introduction it should be clearly stated emission/beam/ brightness of what kind of laser can be improved following your ideas.

- Response:

Thank you for your valuable feedback. We acknowledge the need for a clearer introduction and have revised it accordingly. Our focus is now on the fundamental aspects of controlling chaotic beam dynamics in B-class lasers, specifically through induced periodic structures. This approach is explored using membrane shape active medium type lasers, selected for our experimental convenience. We've clarified the role of brightness as an indirect indicator of interaction between virtual photonic crystals and transverse modes, offering a more targeted introduction to our hypothesis.

For the sake of scientific discussion we can expand a bit. There is the fundamental aspect and the technical aspect. Our motivation is associated with the fundamental aspect of controlling the chaotic beam dynamics using induced periodic structures inside the cavity of a B-class laser. The problem is that technically we can explore this in the small subset of membrane shape type lasers, due to the convenience of being able to prototype the gain pattern using the tools available to us.

Our intuition tells us that it is not important what kind of active media we will use as long as we can introduce enough gain, meaning far beyond the threshold for excited higher-order transverse modes that compete for the population inversion. Moving forward, we must be able to create the periodic distribution of the complex part of the refractive index (gain) to form a virtual photonic crystal that will interact with the beam and surely affect the mode competition.

This leads us to technical aspect. We cannot measure the phase and intensity of different transverse modes being excited simultaneously. The time resolution required and complexity of interpreting the composition of transverse patterns is extreme. However, measuring Brightness as opposed to analyzing each mode of a multimode beam itself, is doable. Therefore, we use Brightness as an indirect indicator of the interaction between a virtual photonic crystal and transverse modes of the cavity.

So, in summary, as long we can manage a reasonable control case, such as homogeneously pumped laser media, which we can compare to the vs periodically pumped laser media, we can test our hypothesis.

We feel that it would be overwhelming to the reader to go into such detail, as there are very little experts that could analyze such concepts. Mainly, prof. K. Staliunas in our group is working on it for many years and with the use of the single longitudinal mode laser model was able to approximate the actual dynamics we observed experimentally in our previous experiments. We never found a predictive model beforehand.

- Comment by the Reviewer:

2. There is missing the definition of brightness in introduction. In whole paper you should use a single measure of the improvements you deserve: beam quality, or brightness or high order modes discrimination.

- Response:

We thank the Reviewer for the comment. We understand that we have to be as specific as possible about the definitions we use early on in the text.

Now the relevant introduction section reads:

… M2 [1]. It characterizes how a particular beam's beam parameter product (proportional half-angle divergence θ times the smallest observable radius ω/ 2) compares to that of a diffraction-limited Gaussian beam. In addition, laser beam output power P divided by the beam quality factor M2 approximates the beam brightness Br. Assuming a circular Gaussian beam characterizable in two directions x and y: Br ∝ P/M2x M2y [2, 3]. In the context of classical laser concepts, one can usually increase the pump input into a laser cavity, but an increase in output power might occur together with the decrease in beam quality (increase of M2), and therefore brightness does not scale trivially. Oppositely, it might even decrease as observed for microchip solid-state lasers [4 ,5] and semiconductor systems [6 ,7]. It is the result of exceeding the generation threshold for higher-transverse modes characterized by a higher divergence. In the absence of a limiting mechanism, such as optical breakdown, and a complicated cavity designed that compensates for it, it is always observable in B-class lasers at some pump power regardless of the way population inversion is achieved [8 , 9]. However, when and to what extent these effects are observable depends on the type of active medium, cavity configuration, pump parameters, and so on.

- Comment by the Reviewer:

3. You should not introduce your own names/definitions (L44*). Surface emitting semiconductor lasers* what it is ? Semiconductor surface emitting laser can be VCSEL, VECSEL, MECSELs, PhCSEL. Ref 26 paper by Guina et al., well describes what is the VECSEL, It is clear that the arrays can not be fabricated with VECSELs, ref. 28 by Broda et al., describes the MECSEL. VECSEL and MECSEL are not used for data transfer (L45) ref 22 by Alford et al. is not suitable here, do not support VECSEL application for data transfer.

- Response:

We thank the Reviewer for pointing out inconsistencies. This was a general statement to differentiate solid state lasers like bulk crystal, fiber and disk lasers. Even though VECSELs are the semiconductor equivalent of a solid state disk laser. Up until the mentioning of VECSELs and MECSELs we consider the electrically pumped VCSELs as the initial device. Later, we introduce VECSELs to specify the limitations of power, and how VECSELS with optical pumping give higher powers.

Changes are made to specify the VCSEL at the start of the paragraph by removing the word "semiconductor". Now the listed applications are correct, while specifying VCSELs as the emission source. Also, this new description now matches the context of 2D arrays.

In the same paragraph, optically pumped versions are mentioned with their cavity structure specified:

"These versions are typically pumped with a laser diode featuring its specific transverse intensity profile. Additionally, one of the cavity mirrors is separated from the structure and a concave output coupling mirror is used to stabilize the cavity and shape the mode."

- Comment by the Reviewer:

4. The VECSEL and MECSEL use external cavity in most cases enclosed by concave dielectric mirror which position determine the beam quality. The dielectric mirror curvature sets the focus size. Focus size together with pump spot determine those laser emission power.

- Response:

Yes, we agree with the Reviewer, that in most cases a concave dielectric mirror is used, and its position (resonator length) determines the mode size. In this paper two setups were tested. One was the more conventional with a concave dielectric mirror with the pump size deliberately larger than the fundamental mode size of the resonator to see the formation of other modes. The other tested case was with a flat mirror in a Fabri-Perot resonator setup. In one sense this forms the plano-plano VCSEL type of resonator structure, but uses optical pumping.

- Comment by the Reviewer:

5. VCSEL and PhCSEL are monolithic. The VECSEL and MECSEL are opticaly pumped wheras the VCSEL and PhCSEL are electrically pumped. In case of the VCSEL the beam quality is limited by current crowding along the circular contact. This current crowding makes the spatial (lateral) gain distribution in VCSEL ununiform. The photonic crystal in PhCSEL is a way to improve the beam quality (but the mode structure of PhCSEL is more complicated issue). Ref 30 by Peckus et al. is no suitable here tray rather a paper by Susumu Noda leader of first PhCSEL research team *Nature Photonics* **volume 8**, pages 406–411 (2014), for instance.

- Response:

We thank the reviewer for clarifying the differences between such structures. For the convenience of the reader, we included the references suggested above in context of spatially structured control.

- Comment by the Reviewer:

6. VCSEL has two DBR from both side of active region. VECSEL has one DBR, MECSEL has no single one. MECSEL was called DBR-free laser by Yang, Zhou, et al. "Optically pumped DBR-free semiconductor disk lasers." *Optics express* 23.26 (2015): 33164-33169. https://opg.optica.org/oe/fulltext.cfm?uri=oe-23-26-33164

- Response:

We agree with the Reviewer, in our case a non-standard structure of the semiconductor laser used. It is relatively novel. “Membrane” is a membrane here because it is transparent to the pump light from both sides and is a suspended structure. “Membrane” also refers to the fact that thinning/removal of the substrate must be done to produce such devices. Yes, the first reported types of MECSELS did not have DBRs on both sides (although AR layer on the MECSEL is also a DBR structure). They retain this AR structure on both sides for the oscillating and pumping wavelengths. This ambiguity is also why initially the commercial name of the structure was used - MEXL (GmbH 21 semiconductors).

Please see our response below, where we continue to discuss this topic.

- Comment by the Reviewer:

7. MECSEL name was introduced by Kahle what was accepted by the research community because of the symmetry with the previous designs VCSEL, VECSEL, MECSEL
Kahle, Hermann, et al. "Semiconductor membrane external-cavity surface-emitting laser (MECSEL)." *Optica* 3.12 (2016): 1506-1512. https://opg.optica.org/optica/fulltext.cfm?uri=optica-3-12-1506

- Response:

Yes, we agree with the Reviewer that this is the historical context. However, when compared to other already accepted names – MECSEL is the closest, due to the transparent layer allowing inline pumping, and the diamond heat spreaders on both sides of the active layer. Other authors actively working on the developing of MECSELS emphasize that the main property of MECSEL's is not the lack of DBR structures on the structure. The main point is the lack of a "intracavity" DBR. In our context, this is the important property.

Please see ref. now included in the text near the MECSEL definition:
Daykin, J., Woods, J. R. C., Bek, R., Jetter, M., Michler, P., Mills, B., Horak, P., Wilkinson, J. S., & Apostolopoulos, V. (2023). Bi-frequency operation in a membrane external-cavity surface-emitting laser. PLOS ONE, 18(7), e0289223. https://doi.org/10.1371/journal.pone.0289223

- Comment by the Reviewer:

8. PhCSEL state for Photonic Crystal Surface Emitting Laser

- Response:

We thank the Reviewer for noticing the missing word in the abbreviation of PhCSEL to Photonic Crystal Surface Emitting Laser. We corrected the abbreviation to be in the more common format.

- Comment by the Reviewer:

9. I am nor sure whether the laser you describe should be called MECSEL. You use a semiconductor membrane but the cavity you build is different then standard used by Yang, Kahle or Broda in papers referred above.

- Response:

We agree with the Reviewer that the cavity is not standard. The manufacturer (21 semiconductors) of the semiconductor membrane also called them membrane external cavity lasers (MEXLs), also used mostly with a concave output coupling mirror. Whereas in our case a flat output coupling mirror is used that is a more unique design, not examined before. So maybe, it in the future it could be characterized as a subtype of MECSELs.

- Comment by the Reviewer:

10. I would advise you to read and consider to mention in your introduction a paper by Iakovlev et al. this paper is widely cited and describes by people involved in MECSEL research. It describes a design quite similar to the one you investigate. Compare your introduction and the one by Iakovlev. Iakovlev do not describe all the possible lasers architectures as you do but provides only the information which makes the reader to understand the improvements proposed by author of the paper Iakovlev, V., et al. "Double-diamond high-contrast-gratings vertical external cavity surface emitting laser." *Journal of Physics D: Applied Physics* 47.6 (2014): 065104. https://iopscience.iop.org/article/10.1088/0022-3727/47/6/065104

- Response:

We thank the Reviewer for pointing out this context. We agree with the Reviewer that the structure used in our experiments is similar to the Type 2 structure mentioned in the Iakovlev V. paper. In both cases diamond heat spreaders are on both sides, and cooling is done from around the structure. This also allows for inline pumping. Instead of high contrast grating mirrors our structure has a dichroic DBR on one side that reflects the oscillating wave and passes the pump and is not structured in the transverse direction. However, the HCG structure as stated exhibits polarization discrimination whereas our used structure does not have such properties. A change in the output polarization was visible with a change in temperature.
The reference suggested was incorporated in the text.

- Comment by the Reviewer:

Errors to be corrected:

For a more spatially uniform laser microfabrication, a flat-top beam gives better the best results and more best control [2,3]. For fabrication high-aspect-ratio structures, a Bessel beam is required [4].
I would delete the words: "more" because I precedented sentences you say nothing about microfabrication its uniformity and its control, so what does it mean here "more" ? The word more serves to compare, for instance, you have something uniform then you do something special and it became more uniform.

- Response:

We thank the Reviewer for noticing and pointing out this mistake. We amended the text:

"...ablation process as compared to a Gaussian pattern...."

- Comment by the Reviewer:

L26 ***One is to shape the beam freely propagating behind the laser, to suit one's needs [5], and another is to shape the pump beam to impose a different gain distribution and gain guiding in the resonator.*** This sentence is wrong because 1) the ward behind is unsuitable here (please check it meaning in a dictionary https://www.merriam-webster.com/dictionary/behind) consider ***beam freely propagating outside the laser resonator,***

- Response:

We thank the Reviewer for the clarification. Changed to the suggested word "outside".

- Comment by the Reviewer:

2) the lasers are not necessary optically pumped. Here you write about the pump beam for the first time. In precedent sentences you should state that you will concentrate on optically pumped lasers.

- Response:

We thank the Reviewer for noticing. Substantial changes were made to the introduction. Augmented the text: There are good reasons to consider laser beam brightness and transverse mode behavior. For instance, it is well known that beam quality is important for micromachining [10]. For such applications, low-brightness laser sources cannot be used efficiently. However, they can be used to pump lasers as in the case of the application of pump laser diodes [11 , 12]. The achievement in spatial quality and brightness of the optically pumped laser trumps the power losses that would occur if one would simply spatially filter the laser diode beam.

- Comment by the Reviewer:

3) **Shaping the pump beam to impose a *different gain distribution*** is true but
and gain guiding in the resonator -is true only when the gain medium fill-up whole resonator what is not true, for instance, in disc lasers, also the pump beam can change the index of the gain medium thus change the guiding effect (but not gain guiding)
Consider: ***One is to shape the beam freely propagating outside the laser resonator, to suit one's needs [5], and another is to shape the pump beam to impose a different gain distribution and/or guiding in the resonator.***
In my previous review of your paper I advised you to concentrate in the introduction on optically pumped disc laser this would help you to be precise.

- Response:

We thank the Reviewer for the suggestion. The relevant text was changed to the suggested form.

- Comment by the Reviewer:

L28 ***Technically, this approach facilitates the light interaction with the gain media without mechanical or electrical manipulation of the resonator.*** The word light is necessary here. Reader has to know what interacts.

- Response:

We thank the Reviewer for the correction. Added the word “light” for clarity.

- Comment by the Reviewer:

L45 The sentence: *Their ability to emit light from the surface instead of from the edge (in more common semiconductor lasers) allows them to be clustered into large 2D arrays.* Is not true, VCSELs can be fabricated as 2D array but VECSEL do not. VCSELs are electrically pumped VECSELs optically !

- Response:

We agree with the Reviewer. The mentioned sentence refers to the more general field of surface emitting lasers (that includes VCSELS), not only to optically pumped VECSELs and/or MECSELS. We clarified the sentence in question to referrer to the specific case for electrically pumped VCSELs.

- Comment by the Reviewer:

L47 *A vertical surface-emitting laser comprises a thin amplifying medium made from quantum wells with Bragg mirrors formed on both sides to form a resonator [23,24].* This is not true, please read the references you provide! The VECSEL has only one DBR ! The MECSEL do not have the DBR at all !

- Response:

We thank the reviewer for noticing inconsistencies. Specified that the structure was of that form for VCSELs. MECSEL have AR coatings that are fabricated in the same manner. They are made from a Bragg structure of alternating refractive index material. And in our case the MECSEL also has 1 HR DBR structure acting as one of the cavity mirrors.

- Comment by the Reviewer:

L50 *The short resonator design leads to gain guiding and index guiding effects [25,26].* This is not true ! VECSEL are type of disc laser with thin (usually um) gain medium and large (usually many cm long) external cavity. The light is controlled by external concave mirror, not gain or index guiding in a semiconductor heterostructure.

- Response:

We thank the reviewer for noticing. L50 was removed. Amendments have been made to the text in regards to the VCSELs to read: “In these lasers, transverse modes form due to the pump profile and how the charges are guided through the cavity [39]”.

This is mentioned for the case of a flat-flat (flat-parallel) cavity design, typical for electrically pumped VCSELs and used in our cavity. Therefore, the cavity itself does not create modes. A possible thermal lens from the pump profile stabilizes the system.

- Comment by the Reviewer:

L51 *In these lasers, transverse modes form due to the pump profile* (this is true) *and not from the geometrical structure of the cavity and the output coupling mirror* (this is not true !) . In VECSEL and MECSEL the modes are determined by external cavity, that is by output coupling mirror position !

- Response:

This question is related to previous answers. A curved OC mirror was not used in this part of the experiments. Due to the flat-flat configuration the mode stabilization is due to the thermal lens from the pump profile. It is only in the later part where it is mentioned that the resonator selects the oscillating modes.

- Comment by the Reviewer:

L 53 *Vertical external-cavity surface-emitting lasers (VECSELs) and their newer versions, the membrane external cavity surface emitting lasers (MECSELs) with the cavity extending from the monolithic semiconductor chip (containing the back mirror and active media), have the ability to both have higher beam quality and higher output powers [28] when compared to monolithic designs.*
To make this sentence true change to
Vertical external-cavity surface-emitting lasers (VECSELs) and their newer versions, the membrane external cavity surface emitting lasers (MECSELs) have the ability to both have higher beam quality and higher output powers [28] when compared to VCSEL monolithic designs.

- Response:

We thank the Reviewer for the correction. To improve clarity, we changed the ordering of words in the way suggested above.

- Comment by the Reviewer:

L64 The PhCSEL is not VECSEL with photonic crystal. VECSEL is optically pumped PhCSEL is electrically pumped. VECSEL without PhC achieve higher power and better beam quality then PhCSEL !

- Response:

We have amended the text not to emphasize this part. In conjunction with the following comment, the text now focuses on comparing PCELS and VECSEL in terms of performance. Please see the following comment and response.

- Comment by the Reviewer:

Compare the ref 26 and papers by Susumu Noda https://www.nature.com/articles/nphoton.2014.75 this paper has 390 citation.

- Response:

We agree with the Reviewer that this is good context to be introduced for the reader, and have done so. Now the text reads:

The other alternative is photonic crystal structures integrated with the gain-medium as in PCSELs [48, 49]. PCELs are well-known for their capacity to generate a high-power output with an impressive beam quality, particularly in single-mode operation, which is a major improvement compared to traditional surface-emitting lasers. However, due to the complex photonic crystal structures and fabrication techniques, they have difficulty sustaining this high-power output across a wide range of applications. On the other hand, VECSELs [50] offer a broader spectral range and flexibility for various applications, such as atom physics and dermatology, but they have traditionally had issues with thermal management and producing high power output in a compact form, which have been gradually addressed with technological advances.

- Comment by the Reviewer:

L66 ref 34. By Lukowski et al. is not about photonic crystal on top of VECSEL, The optical element in Lukowski VECSEL resonator change the beam mode but not improves the brightness
the ref 35 is also unsuitable here try the paper by Susumu Noda
https://www.nature.com/articles/nphoton.2014.75

- Response:

Yes, they use a separate intracavity element to shape the output mode. We moved the reference to the discussion about intracavity modulation and replaced the previous reference here with Susuma Noda et al. reference.

- Comment by the Reviewer:

L70 *In this work, we investigate whether a novel mode of operation can be achieved via structured optical pumping. A diode-pumping approach and a surface-emitting membrane semiconductor active medium characterize our particular approach.* Those two sentences should be corrected. You may try

In this work, we demonstrate that a novel ***brightness*** *of a disc laser mode of operation can be achieved* ***improved*** *via structured optical pumping****. For this purpose we usie modified*** *diode-pumping* ***beam*** *approach and a surface-emitting membrane semiconductor active medium characterize our particular approach.*

- Response:

We thank the Reviewer for the suggestion, and we have amended the text to read as per the suggestion above.

- Comment by the Reviewer:

L91 a word *laser* or *amplifier* is missing after “broad area semiconductor” broad area semiconductor laser (or amplifier) makes sense. Broad area semiconductor does not makes sense, sound as description of a wafer.

- Response:

Thank you, the text was amended with “amplifier" to specify the semiconductor structure.

- Comment by the Reviewer:

L114 what was the mode/fiber dimeter of your laser pump ?

- Response:

The used fiber core diameter is 400 µm as mentioned in the materials and methods section. Experimental section was augmented with the information on the fiber diameter was added to the experimental setup section.

- Comment by the Reviewer:

There are an errors in the caption of Figure 1. There are no PP, BS in the figure a
An active area is encased in ***head*** *spreaders* should be heat

- Response:

We thank the Reviewer for noticing and fixed the caption of the figure.

- Comment by the Reviewer:

L122 should be propagation of the laser beam Laser itself do not propagates !

- Response:

We thank the Reviewer for noticing. The word beam was added for correction.

- Comment by the Reviewer:

L159 there is no verb in the sentence The acquired conversion efficiency of η = 25 %.

- Response:

We thank the Reviewer for the correction, we changed the word “of” to “was”.

- Comment by the Reviewer:

L165 should be The oscillating resonator fundamental mode must be… not The oscillating fundamental resonator mode must be…

- Response:

Thank you very much for the suggestion. We have amended the wording order.

- Comment by the Reviewer:

L170 please correct “slight decrease in energy **power** in the central “

- Response:

We thank the Reviewer for the correction. The word was changed to power.

- Comment by the Reviewer:

L172 please correct “from **with** an increase in the pump power is shown in (Supplementary video 1).

- Response:

Thank you very much for the suggestion. We have amended “from” to “with”.

- Comment by the Reviewer:

L282/283 Therefore, the resonant mode size decreased and was only coupled to the fundamental mode. Correct this sentence resonant mode cannot couple to fundamental mode

- Response:

We thank the Reviewer for noticing, the text was changed to: Therefore, the resonant mode size decreased in the flat-flat resonator configuration.

- Comment by the Reviewer:

L287 correct …resonating beam’s energy **power** onto…

- Response:

We thank the Reviewer for the correction. We have amended the section to read: “<…> power <…>”.

MDPI

Article

Spatially structured optical pump for laser generation tuning

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Abstract: The main goal and essential parameter of laser light conversion is achieving higher laser brightness. That is the main reason why we take one light source to pump another. For every application, the desired laser beam must have the highest available beam quality and highest achievable power. Usually, by increasing one parameter, you incur a loss in the other. Here, we present a method for delaying the reduction in beam quality by using a spatially structured optical pump for a membrane external cavity laser resonator. A slight increase in brightness is achieved under the same focusing conditions just by changing the pump intensity profile. A controllable output laser mode can be achieved by using a dynamically changing pump pattern.

Keywords: spatial beam shaping; modulated pump; MECSEL

Citation: Kontenis, G.; Gailevičius, D.; Taranenko V.; Staliūnas, K. Spatially structured optical pump for laser generation tuning. *Nanomaterials* **2023**, *1*, 0. https://doi.org/

Received:
Revised:
Accepted:
Published:

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1. Introduction

From the first construction of lasers, many improvements were performed to fit the growing number of applications. Generating radiation of different wavelengths, controlling and shortening the pulse duration, increasing the conversion efficiency, and narrowing the generation spectra are just some of the directions of developing the laser. One property of the laser that is steadily improving is the beam's high spatial quality M^2 [1]. It characterizes how a particular beam's beam parameter product (proportional half-angle divergence θ times the smallest observable radius $\omega/2$) compares to that of a diffraction-limited Gaussian beam. In addition, laser beam output power P divided by the beam quality factor M^2 approximates the beam brightness Br. Assuming a circular Gaussian beam characterizable in two directions x and y: $Br \propto P/M_x^2 M_y^2$ [2,3]. In the context of classical laser concepts, one can usually increase the pump input into a laser cavity, but an increase in output power might occur together with the decrease in beam quality (increase of M^2), and therefore brightness does not scale trivially. Oppositely, it might even decrease as observed for microchip solid-state lasers [4,5] and semiconductor systems [6,7]. It is the result of exceeding the generation threshold for higher-transverse modes characterized by a higher divergence. In the absence of a limiting mechanism, such as optical breakdown, and a complicated cavity designed that compensates for it, it is always observable in B-class lasers at some pump power regardless of the way population inversion is achieved [8,9]. However, when and to what extent these effects are observable depends on the type of active medium, cavity configuration, pump parameters, and so on.

There are good reasons to consider laser beam brightness and transverse mode behavior. For instance, it is well known that beam quality is important for micromachining [10]. For such applications, low-brightness laser sources cannot be used efficiently. However, they can be used to pump lasers as in the case of the application of pump laser diodes [11,12]. The achievement in spatial quality and brightness of the optically pumped laser trumps the power losses that would occur if one would simply spatially filter the laser diode beam.

There is an alternative case where a Gaussian shape is not the best option for all applications, and other types of transverse intensity patterns are desirable. For a more uniform laser ablation process as compared to a Gaussian pattern, a flat-top beam gives better results and more control [13,14]. For high-aspect-ratio structures, a Bessel beam is required [15]. However, classical resonators are designed to output a fundamental Gaussian mode and various beam conversion techniques must be used to convert the beam into the desirable pattern [16]. The aforementioned approach of transforming the freely propagating beam outside the laser to suit one's needs [17,18] is not the only option. Another, a more exotic choice, is to shape the pump beam to impose a different gain distribution and/or guiding in the resonator. Technically, this approach facilitates light interaction with the gain media without mechanical or electrical manipulation of the resonator. In addition, it is possible to shape the beam inside the cavity, forcing certain modes to resonate and dominate over others (intracavity modulation). Extracavity modulation is more related to better control of thermal effects [19] and energy extraction [20]. Intracavity is mostly used for mode selection where gain or loss can be spatially controlled to select the desired mode [21–24] of the laser output, and higher energy extraction efficiency from the lasing medium [25,26], by using top-hat or flat-top beam profiles when the beam propagates through the gain region. The selection of passive [27] or active [28,29] elements can be used. Intracavity modulation is beneficial because the resonator acts as a filter and purifies the oscillating mode [30–33]. For example, the flat-top beams can be formed by reshaping the propagating beam using diffractive or refractive methods. This gives a flat-top profile that results in a uniform intensity pattern in the vicinity of the focusing lens focal plane. Using intracavity structuring, a shape-invariant flat-top beam can be achieved from a mixing of LG_{00} and LG_{01} beams [34]. Amplitude modulation inside the laser cavity has been shown by inducing losses with a wire to produce Hermite-Gaussian modes [35].

The compact vertical cavity surface-emitting lasers (VCSELs) are gaining more and more interest for their potential applications in data transfer and metrology [36]. Their ability to emit light from the surface instead of from the edge (in more common semiconductor lasers) allows them to be clustered into large 2D arrays. A VCSEL comprises a thin amplifying medium made from quantum wells with Bragg mirrors formed on both sides to form a resonator [37,38]. In these lasers, transverse modes form due to the pump profile and how the charges are guided through the cavity [39]. Vertical external-cavity surface-emitting lasers (VECSELs) [40] and their newer versions, the membrane external cavity surface emitting lasers (MECSELs) have the ability to both have higher beam quality and higher output powers [41,42] when compared to VCSEL monolithic designs. These versions are typically pumped with a laser diode featuring its specific transverse intensity profile. Additionally, at least one of the cavity mirrors is separated from the structure and a concave output coupling mirror is used to stabilize the cavity and shape the mode. These structures should have better power scalability due to much smaller thermal stresses [43] and better thermal management [44].

Photonic crystal (PhC) spatial filters are a potential solution to suppress multimode operation in microcavity lasers, increasing the output beam spatial quality and its brightness [45–47]. The other alternative is photonic crystal structures integrated with the gain-medium as in PCSELs [48,49]. PCELs are well-known for their capacity to generate a high-power output with an impressive beam quality, particularly in single-mode operation, which is a major improvement compared to traditional surface-emitting lasers. However, due to the complex photonic crystal structures and fabrication techniques, they have difficulty sustaining this high-power output across a wide range of applications. On the other hand, VECSELs [50] offer a broader spectral range and flexibility for various applications, such as atom physics and dermatology, but they have traditionally had issues with thermal management and producing high power output in a compact form, which have been gradually addressed with technological advances.

Lastly, the most exotic periodic structures can be created by interfering with multiple beams at an angle. Colloidal quantum dots affected by such an intensity pattern

exhibit a self-diffraction effect. The dimensionality of the photonic structure can be controlled by changing the polarization of the interfering light, giving dynamic control of the structure[51,52]. In this work, we demonstrate that the brightness of a disc laser mode of operation can be improved via structured optical pumping. The change in brightness is an indirect observation of transverse mode interaction with the periodic gain structures intentionally induced in the cavity. For this purpose, we use a modified diode-pumping beam approach and a surface-emitting membrane semiconductor active medium to characterize our particular approach.

2. Methodology and the laser setup

2.1. Models for phase mask selection

We used amplitude modulation to shape the intensity profile of the pump beam. By shifting the phase of close-by pump beam regions, destructive interference then forms beam shapes with a dip in intensity. Pattern with a periodically changing intensity acts as an array of coherent laser sources similar to [53]. With this approach, the efficient, coherent combining of 16 solid-state laser channels operating at single transverse Gaussian modes has been shown with an efficiency of 87 %. The reported beam quality of the combined beam was $M^2 = 1.3$, meaning that the beam quality remained the same but with an increase in power. Talbot resonators [54,55], have been shown to phase-lock separate yet coherent sources. Non-phase-locked lasers usually generate high power outputs but are not very bright, whereas phase-locked lasers also offer good beam quality. The Talbot effect is a phenomenon in which a coherent periodic structure replicates itself at periodic intervals. In the ideal case, after the Talbot distance, the initial field would reimage iteself. The Talbot distance is given by:

$$Z_T = \frac{2d^2}{\lambda}, \tag{1}$$

where λ is the wavelength d is the transverse spatial period. This effect has a major influence on the structure of the transverse mode when it arises inside the cavity of a laser array [56]. In our case, the pump beam's linear periodic intensity distribution acts as multiple coherent emitters. The spacing period can be adjusted by altering the relevant hologram. We take a similar approach to that employed in [57], where two-dimensional, regularly arranged electrical contacts were produced on a broad area semiconductor (BAS) amplifier. In the case of optical pumping, the spatial structure of the pump beam determines the transverse periods $\Lambda_\perp$, and the length of the resonator is used as the longitudinal period $\Lambda_\parallel$. As the laser oscillates in the cavity with each round trip, the beam is affected by the intensity distribution of the pump source. The pump source determines the gain distribution and, therefore, the amplitude modulation. This should result in a decrease in divergence due to the feedback between the pump structure and the resonating mode, which can be represented by the parameter Q:

$$Q = \frac{2\Lambda_\perp^2 n}{\lambda \Lambda_\parallel}. \tag{2}$$

The concept of a periodically structured pump integrated into a laser cavity is based on the selective deflection of the angular components of light passing through a two-dimensional photonic structure. The angular components that are resonant with the transverse and longitudinal periodicities of the structure are diffracted efficiently and are deflected away from the zero-diffraction order of the transmitted beam. Previous studies have demonstrated that periodic gain/loss modulation on the wavelength scale can lead to specific beam propagation effects, such as self-collimation and spatial (angular) filtering. For longer resonators, the beam profile is mainly determined by the most amplified mode, while for shorter or moderate lengths, a comprehensive analysis of the mode growth reveals that other modes also contribute to the final beam shape. By selecting the appropriate spatial periods, it is possible to narrow the central far-field component while significantly

improving the spatial structure of the amplified beam. Additionally, by shaping the pump beam a good spatial overlap between the pump and the desired mode can be achieved, thus forcing the laser oscillations in that transverse mode

2.2. Experimental setup

Here, we used a 400 μm core diameter fiber-coupled $\lambda = 808$ nm laser diode as the pump source. It can be run at continuous-wave (CW) or quasi-continuous-wave (QCW) regimes using pulse width modulation. A thin membrane external cavity surface emitting laser (MECSEL) was used as the active medium with a thickness of 1 μm Figure 1(b). We used a liquid crystal on a silicon spatial light modulator (SLM) to act as the beam-shaping element of the pump beam. It is a two-dimensional $1980x1024$ pixel array with a pixel size of 8 μm that allows control of the phase of the laser beam by delaying it locally with each pixel. This makes it possible to distort the laser wavefront, which is a surface of the same phase. This changes the further propagation of the laser beam and due to the interference, a dynamically controlled and variable intensity distribution is formed. It is possible to locally reduce the intensity and perform amplitude modulation of the laser with SLM. It can be done by exploiting the fact that adjacent pixels shifted anti-phase, allowing destructive interference generation. A magnifying telescope of two lenses, 1000 mm and 30 mm/15 mm was used in a 4F setup to scale and relay the structured intensity distribution to the active area of the MECSEL chip. A QCW regime was used for experiments with a pulse duration of 200 μs and a repetition rate of 500 Hz. When a flat output coupling mirror is used, the entire resonator is only stabilized by the thermal lens inside this very thin MECSEL chip. Although the structure is 1 mm thick with an active area of just around 1 μm and fast heat dissipation, the thermal lens still arises and stabilizes laser operation. The flat output coupling mirror (OC) with a reflectivity of 99 % was placed with an air gap of 200 μm for a total physical resonator length of 1.2 mm.

The telescopes used in the experiment were comprised of magnifying 4F systems Figure 2(a), the corresponding pixel count in the amplitude mask on the SLM screen corresponded to a certain size in μm in the focal plane and scaled linearly. The variations of the holograms used in the experiment are shown in Figure 2(b). The main types comprise ring holograms that selectively attenuate the edges of the pump beam or periodic line patterns with varying widths that etch out linear intensity regions.

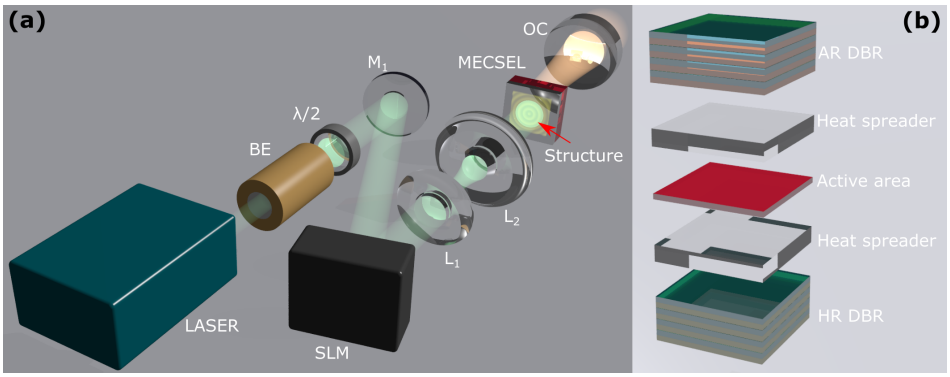


Figure 1. (a) Shows the setup used in this work. Annotations: $\lambda/2$ - half wave phase plate, M - mirror, BE - beam expander, SLM - spatial light modulator, L - lens, MECSEL - membrane external cavity surface emitting laser chip, OC - output coupling mirror. (b) Displays the simplified structure of the MECSEL chip. An active area is encased in heat spreaders and distributed Bragg reflectors (DBRs), where one side acts as the resonator mirror (HR) and the other reduces the resonator losses by reducing reflections (AR).

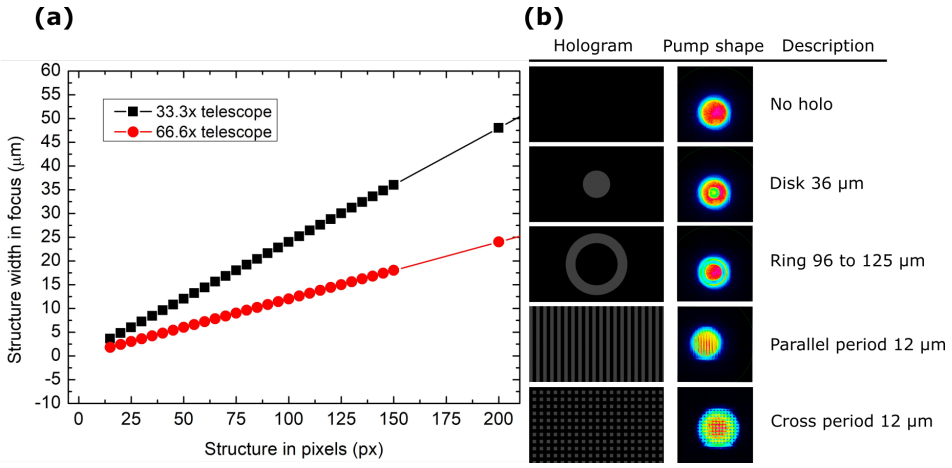


Figure 2. (a) Shows the number of pixels used to generate an amplitude modulation in the near field corresponding to a certain width in the magnified region. (b) shows holograms with their corresponding code names and the resultant pump intensity profile.

3. Results

To see the effects of the structured pump on the active layer itself, the spontaneous emission of the beam shape was visualized onto a CCD beam profiler by using a lens in a double focal length setup (2F2F). As seen in Figure 3 the pump beam shape is visible on the active media. However, the contrast between intense regions and dark regions is not as clear as on the pump beam itself. This can be due to the diffusion of the carriers in the active areas of quantum wells. This limits the pump structures' density before diffusion equalizes the intensity distribution.

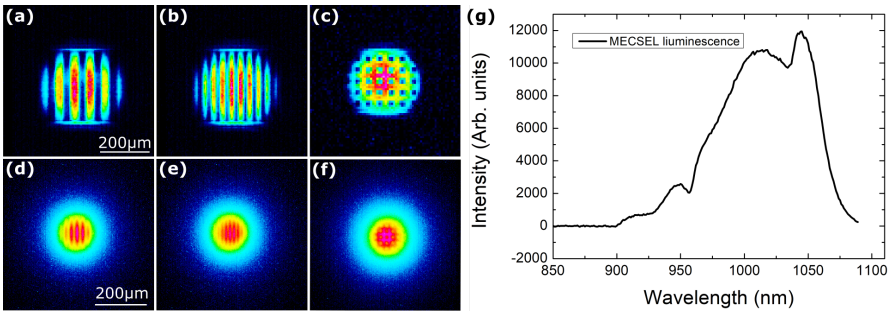


Figure 3. (a)(b)(c) shows the intensity patterns of the pump beam and (d)(e)(f) shows the corresponding spontaneous emission pattern on the MECSEL active layer. The used scaling was 33.3x. (g) shows the typical spontaneous emission spectrum as observed at the pump power of 200 mW.

Due to a large selection of possible pumping intensity shapes, some basic intensity distributions were chosen (Figure 2). One way of modifying the pump beam is by removing the central intense region - a "Disk" hologram achieves this. Alternatively, a "Ring" hologram can apodize and remove the edges. Additionally, some periodic structures can be formed by a repeating linear or a 2D varying modulated and not modulated regions. Because we use amplitude modulation, the part that sees destructive interference also diffracts out of the optical chain's optical axis and doesn't propagate toward the active media. Therefore, if we normalize each used beam shape with the actual optical power impinging on the MECSEL chip, we see that the conversion efficiency remains unchanged regardless of the shape (Figure 4). The beam size on the MECSEL chip was 175 μm from a 66.6x reducing telescope made from a pair of lenses with 1000 mm and 15 mm focal lengths. The acquired conversion efficiency was $\eta = 25$ %. All parameters were measured in the same manner, so systemic errors were identical. The beam width of the output beam was measured at

the focal plane of a 50 mm focal lens. In all cases, the lens was placed 150 mm from the resonator's OC. The far field intensity distribution was measured at two different planes 5 mm and 10 mm away from the focal spot.

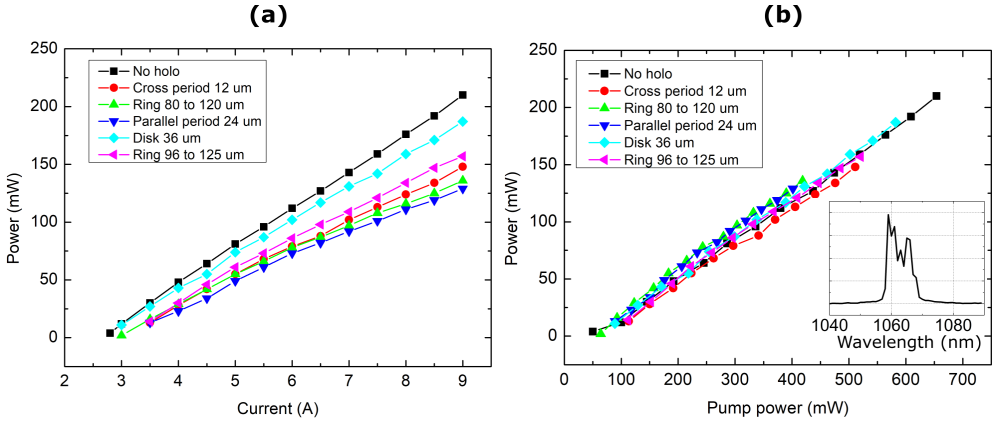


Figure 4. (a) shows the output power based on the pump diode current, while (b) shows the MECSEL laser output power versus the pump beam power incident onto the chip. In the inset on the lower right is a snapshot of the typically observed spectrum of the output beam.

The oscillating resonator fundamental mode must be much smaller than the pump beam in order to get higher-order beam shapes to oscillate. If the fundamental oscillating modes and pump beam sizes match, no higher modes are formed and just a decrease in power is present due to the lower coupling of the beam. They all follow the same pump power generation path with similar divergence and focusing parameters. The output beam mostly remained a TEM_{00} mode with a slight decrease in power in the central region at higher pumping (Figure 5). How the far-field intensity distribution changes with an increase in the pump power is shown in **(Supplementary video 1)**. The shape oscillates by becoming more elliptical in one axes, then becoming circular and then elliptical in the perpendicular. At higher powers, the maxima of the output beam flatten out it no longer is a pure TEM_{00}, there are higher modes mixed in. This gives rise to a decrease in the overall brightness.

For the brightness calculations of the laser beam, the expression used was:

$$Br = \frac{P}{A\Omega} = \frac{P}{\pi\theta_x\theta_y\omega_{0x}\omega_{0y}}, \tag{3}$$

where θ_x, θ_x are the beams divergence and ω_{0x} ω_{0y} are the beam waist at focus for x and y directions respectively. From Figure 6, we can see a brightness peak at a pump power of around 350 mW. Around this power level, the far field of the generated beam started to have a flatter intensity distribution. A further increase in power started to form an intensity dip in the center. This could be the formation of higher-order modes. Because MECSELs have heat spreaders on both sides of the active layer, they inherently form a micro-cavity inside the structure. This has the effect of forming multiple emission peaks at different wavelengths. Therefore, identifying multimode operation from spectral data is not easy. From power conversion characteristics (Figure 4), a linear relation between the output and pump power is visible. Saturation was not reached in this experiment. The only source of a decrease in brightness is the degradation of the quality of the beams. The divergence of the beams increases almost linearly with the oscillations due to the shifting ellipticity in the far field, while the beam's ability to focus initially gets better (Figure 8) and the focal spot gets tighter, but as higher modes start to form inside the resonator, the spot sizes start to increase.

The 1D periodic line pump divergence in Figure 7 shows a peculiar phenomenon in which the divergence of the beam does not appear to change over the period of 12 μm. If we

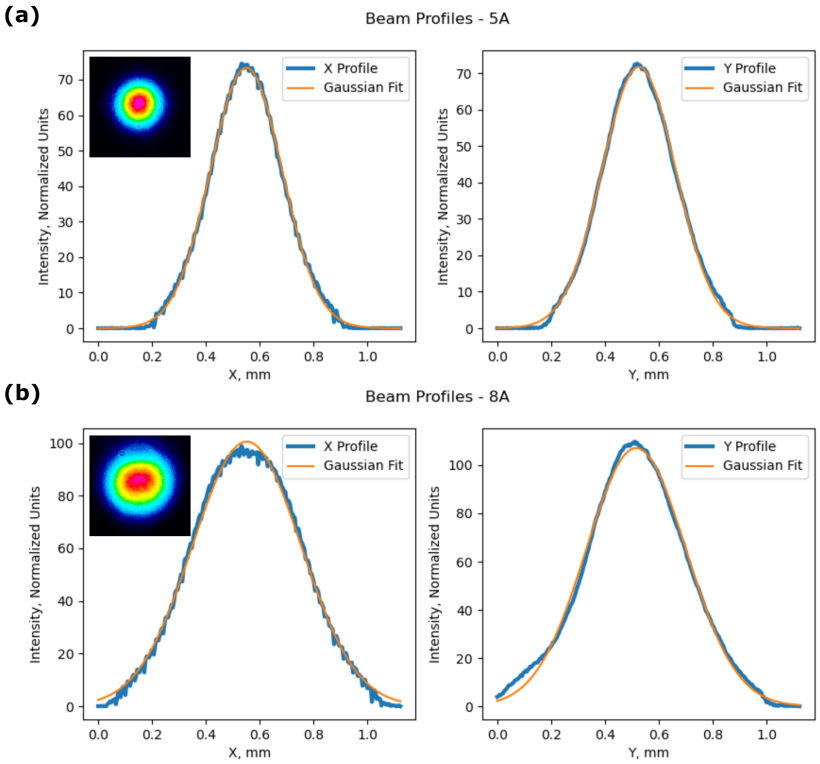


Figure 5. Shows the profile intensity distribution of the generated beam in X and Y cross-section with an average pump power on the active chip area of (a) 5A - 291 mW and (b) 8A - 586 mW.

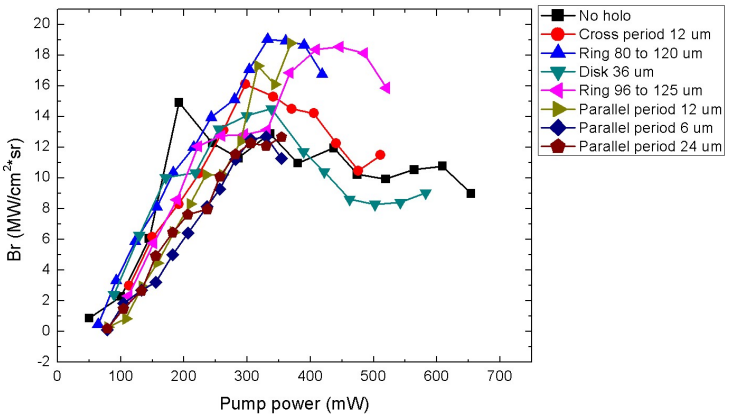


Figure 6. MECSEL laser brightness dependence on pump beam average power. "No holo" is the case where the SLM was used as a reflecting mirror with no modulation.

look back at Eq.2. The cavity comprises a 1 mm long MECSEL structure with a 0.2 mm air gap separating the semiconductor chip and the outcoupling mirror. The detailed structure of the MECSEL is unknown (as far as we can tell it is proprietary), but assuming the average refractive index of 3 we get that: For the case where $\Lambda_\perp = 12\ \mu m$ the longitudinal period is $\Lambda_\parallel = 812\ \mu m$, and for the case where $\Lambda_\perp = 15\ \mu m$, $\Lambda_\parallel = 1269\ \mu m$. Therefore, the stabilization of divergence could be attributed to the matching of the longitudinal and transverse periods. Here, using 6 μm and 12 μm periods is too far from the $Q = 1$ relation. However, the power scaling did not generate clearly visible LG_{01} and higher order modes.

Curved resonator setup. To see a change in the output beam shape a curved OC with a radius of curvature of 100 mm was used instead of a flat that has been mentioned above. This gives a Flat-Concave resonator setup. The resonator length of L = 95 mm gives a mode

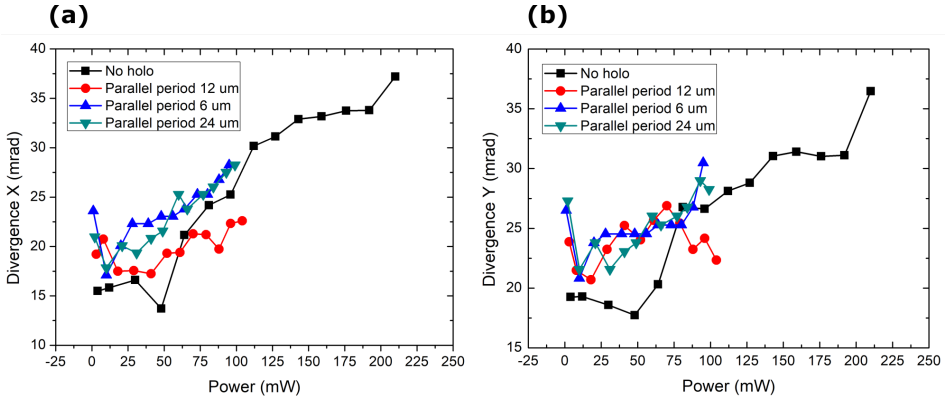


Figure 7. Change in the divergence of the generated laser radiation with power in X and Y direction.

size on the MECSEL chip of $2\omega = 168\ \mu m$. The pump spot from a 30 mm lens is 340 μm and is larger than the fundamental oscillating mode size for the curved mirror case. A curved mirror already selects the modes that will oscillate inside a resonator, but using an elongated pump allows only modes above the threshold to lase. This shape is achieved by a cylindrical lens phase hologram formed on an SLM. Then, by rotating the pump shape with the holograms, we can select sets of transverse modes. The resonator itself determines the shape. An asymmetric pump profile in an ellipse gives rise to asymmetrical modes, essentially getting an elliptical output that follows the pump pattern (Figure 9). The exact output shape does not rotate with the pump exactly; there is some asymmetry in the resonator itself, and one orientation gives rise to a larger ellipticity than the other.

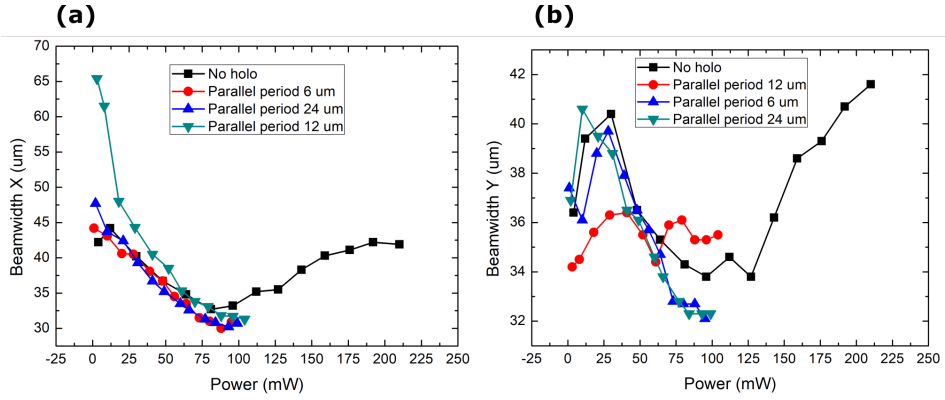


Figure 8. Change in focal beam size of the generated laser radiation with power in X and Y direction.

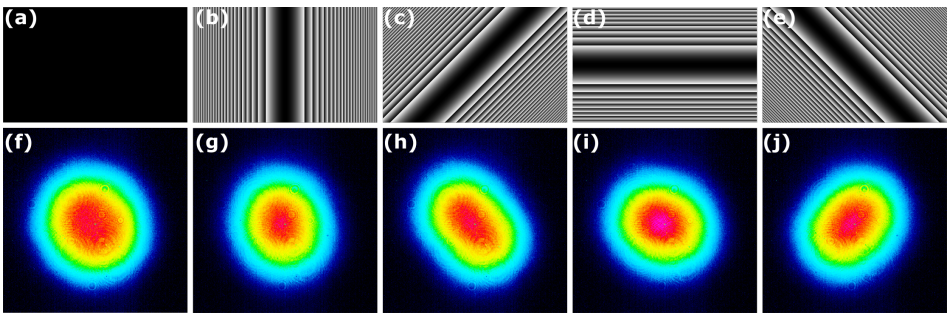


Figure 9. (a)-(e) are the used holograms for shaping the diode pump beam while (f)-(j) are the laser output beam's far-field shape as a result of a rotation in a cylindrical hologram on the pump beam. The corresponding rotations are 0, 45, 90, and 135 degrees.

Another tested beam shape was in the form of transverse LG modes with different topological charges. Such modes were formed using phase holograms with azimuthally changing phase offset, where the topological charge is given by the number of times the phase offset reaches 2π value. While the pump beam was an ever larger LG mode with an increasing topological charge (Figure 10), the generated intensity pattern begins to form 4 maxima in the shape of a spatial mode TEM_{11} instead of a larger ring. The polarization of the output beam remains linear and does not split between the modes. A slight intensity mismatch between the maxima in Figure 10 (i)(j) could be from asymmetries in the optical scheme.

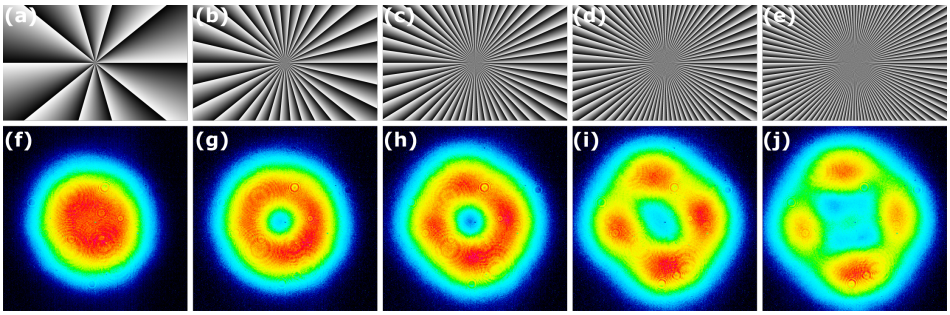


Figure 10. The holograms used for shaping the pump and the resulting MECSEL lasing beam output in the far field. (a)-(e) shows the pump beams phase hologram, while (f)-(j) shows the corresponding generated distribution. The corresponding topological charges are l =10, 30, 50, 70, 100

4. Materials and Methods

The pump laser used for the experiment was a K808DAERN-30.00W electrically pumped diode laser operating at 808 nm from BWT BEIJING and coupled to a 400 μm core multimode fiber. The active media used for the setup was a "21 semiconductors" supplied 21S-M1064-496 MEXL chip that uses an 808 nm pump and outputs 1064 nm. The chip was soldered with an HR Bragg mirror side to the brass plate. A HoloEye SLM PLUTO-2.1-NIR-113 used for beam shaping that has a two-dimensional 1980x1024 pixel array with a pixel size of 8 μm. A Peltier element with a copper plate was used to mount and cool the MECSEL chip during operation. A CCD beam profiler (WinCamD-UCD15, DataRay Inc.) was used to measure the beam. An inline pumping scheme was used with the pump beam shape modulated by the SLM using predominantly checkerboard patterns for amplitude modulation.

5. Discussion and outlook

While being a dynamic optical element, the SLM does give the ability to tune and change the output characteristics of the laser in real-time. Using an SLM for the structured pump has its drawbacks because the pixel size is much larger than the pump wavelength and linearly polarized light must be used as the input. High amounts of magnification are needed to use the entire SLM screen for beam shaping, and focusing it down to appropriate power densities for laser pumping requires a high ratio of focal lengths for the 4F system, making the entire system bulky. This method works as a proof-of-concept with the ability to tune and dynamically modulate the output, not the final design of a compact semiconductor laser. The pixel size can be remedied to some extent by using SLMs with smaller pixels. Using smaller pixels in liquid crystal SLMs can cause an increase in crosstalk between them. This is because the pixels form a continuous grid and the electrical field applied to neighboring pixels affects the phase shift of a single pixel. This information is detailed in [58]. In this experiment, amplitude modulation was predominantly used; therefore, other devices such as a digital micromirror device (DMD) might be a better and faster solution.

The dominant mechanism for the resonant mode formation is defined by the resonator structure/configuration and not the pump beam structure, but however, resonator modes

that do not overlap with the pump beam cannot resonate. A change in the pump beam can selectively choose all modes that overlap with the pump beam. Because the resonator's structure still determines the final oscillating mode, carrier diffusion, and resonator feedback smooth out any pixel cross-talk and intensity fluctuations. Therefore, smaller feature sizes in the pump beam have a small modulation depth and do not influence the laser output.

Although this type of textured pumping does induce a loss in the pump's optical chain, the output power conversion efficiency is not diminished by using a hologram. The output beam comes with a slightly reduced divergence and tighter focusing. After the brightness of the beam has peaked, textured pump-induced generation gives rise to a smaller further reduction in brightness. The observed increase in brightness is obtained because the ring-shaped holograms limit the pump beam diameter on the active medium, in a similar fashion as closing a physical aperture inside the resonator. The total intensity of the beam weakly decreases from the edges, however, the beam divergence can be significantly reduced. If the aperture is too small, it will start to affect the lowest transverse modes, resulting in a decrease in power. The limiting factor in this experiment was the available diode pump power. Therefore, a pure single higher-order mode operation could not be achieved.

Using a lossless approach to create the required pump intensity pattern could further increase the efficiency and usefulness of this method. Further experiments and theoretical simulations are needed to understand better the complex interaction of the non-trivial pump shape and resonant mode coupling.

6. Conclusions

In conclusion, we have shown the output mode modification in two cases: flat-flat and flat-curved resonator configurations. We evaluated the generated beam's output power and propagation parameters. We demonstrated this principle on a diode-pumped membrane external-cavity surface-emitting laser, where the pump beam's intensity profile has been shaped. The flat–parallel configuration of the resonator and pumping from the end favored a Gaussian mode oscillation. We generated a slightly reduced divergence and sharper focusing, indicating an improvement in beam quality, for a given MECSEL output power in the cases where the pump is concentrated in a smaller area. Therefore, the resonant mode size decreased in the flat-flat resonator configuration. We propose a feasible and dynamic scheme to tailor and control the complex spatial dynamics of MECSELs. The mechanism for divergence stabilization is not fully investigated. A possibility could be that the intensity dips introduced in the pump profile can act as attractors concentrating the resonating beam's power onto the optical axis and coupling better to the fundamental mode.

Author Contributions: Conceptualization, D.G. and K.S.; Formal analysis, G.K; Funding acquisition, K.S.; Investigation, G.K.; Methodology, K.S., D.G., G.K.; Project administration, K.S.; Resources, K.S., D.G.; Software, G.K; Supervision, D.G., K.S.; Validation, V.T.; Visualization, G.K.; Writing—original draft, G.K.; Writing—review and editing, V.T. All authors have read and agreed to the published version of the manuscript.

Funding: Authors D.G, G.K., acknowledge funding under the "Universities' Excellence Initiative" program. Author K.S. acknowledges funding from the Spanish Ministry of Science, Innovation and Universities (MICINN) under grant PID2019-109175GB-C2

Acknowledgments: G.K. and D.G. acknowledge dr. Renata Butkutė from the Center for Physical Sciences and Technology for insights into the process of semiconductor laser fabrication and the cooling system.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SLM	Spatial Light Modulator
OC	Output Coupler
CCD	Charge Coupled Device
LG	Laguerre Gauss
VCSEL	Vertical Cavity Surface Emitting Lasers
VECSEL	Vertical External Cavity Surface Emitting Lasers
PCSEL	Photonic Crystal Surface Emitting Lasers
PhC	Photonic Crystal
GL	Gain/Loss
CW	Continuous Wave
QCW	Quasi Continuous Wave
MECSEL	Membrane External Cavity Surface Emitting Lasers
MEXL	Membrane eXternal cavity Lasers
DBR	Distributed Bragg Reflector
BAS	Broad Area Semiconductor
HR	High Reflecting
AR	Anti Reflecting

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