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Non-linear structured light in a self-imaging laser cavity based on III-V semiconductor nanotechnology

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ABSTRACT

We present a classification of the transverse light states observed in a 3D degenerated optical system using a specially design VECSEL based on III-V semiconductor nanotechnology with weak light confinement in matter. A broad transverse area system with low but tunable diffraction combine with saturable absorption is used for light confinement. These light states include CW paraxial spherical coherent beams linearly polarized, conical waves and spatially degenerate coherent light. A first result of a non-linear structuration is also shown.

Keywords: semiconductor laser ; non-linear optics ; structured light ; VCSEL

1. INTRODUCTION

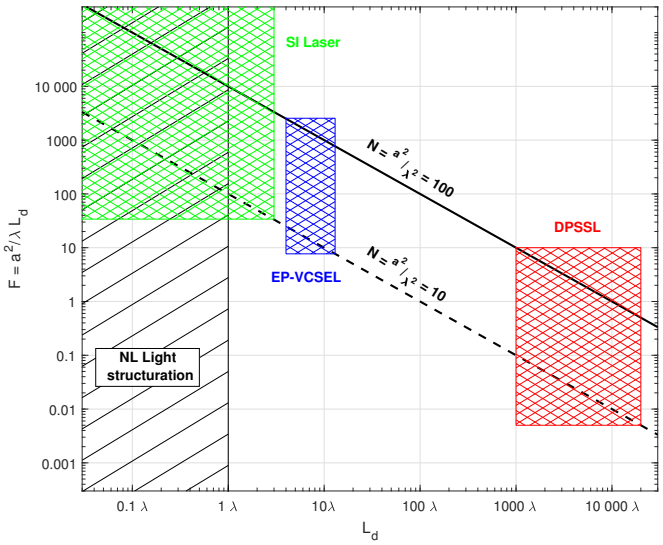


Figure 1. Fresnel number (F) versus diffraction length (L_d) for two different numbers of elementary structure (N) of size λ, "a" correspond to the aperture of the system. Black hatch area correspond to the small diffraction necessary for light structuration. Green hatch area is the operating range for self-imaging laser. Blue hatch area is the operating range for monolithic laser such as electrically pump VCSEL. Red hatch area is the operating range for solid-state laser.

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Classical laser systems, such as solid-state lasers exploit paraxial stable optical cavities with low Fresnel number in strong diffraction regime[1,2] , under weak light-matter interaction to select a single coherent light state. On the other-hand more exotic laser concepts and technologies, like nanolaser, use λ^3 cavity volume with strong light-matter coupling for non-conventional light states generation[3–5] . We aim to design a laser system for spatial non-linear light structuration such as localised state independently addressable. This requires to have a large spatial dimensionality compare to the elementary size of the system and small diffraction, in other word, a system with a large Fresnel number. By adding self amplitude modulation with a saturable absorber we hope to achieve multiple localized state independent from the boundary conditions. From figure 1 we can see that common system such as solid-state laser or EPVCSEL are not particularly well suited for this application, so a novel cavity design in a self-imaging configuration wiht low but tunable diffraction and semiconductor gain mirror / absorber is used to structure different light state. This type of solution can be suited for all optical information processing by being used as bit of information[6,7] . Combining spatial and temporal controllable localized structure can open the way to full optical buffering with $M \times N^2$ memory capacity (N bits matrix in space and M bits matrix in time).

2. EXPERIMENTAL SET-UP

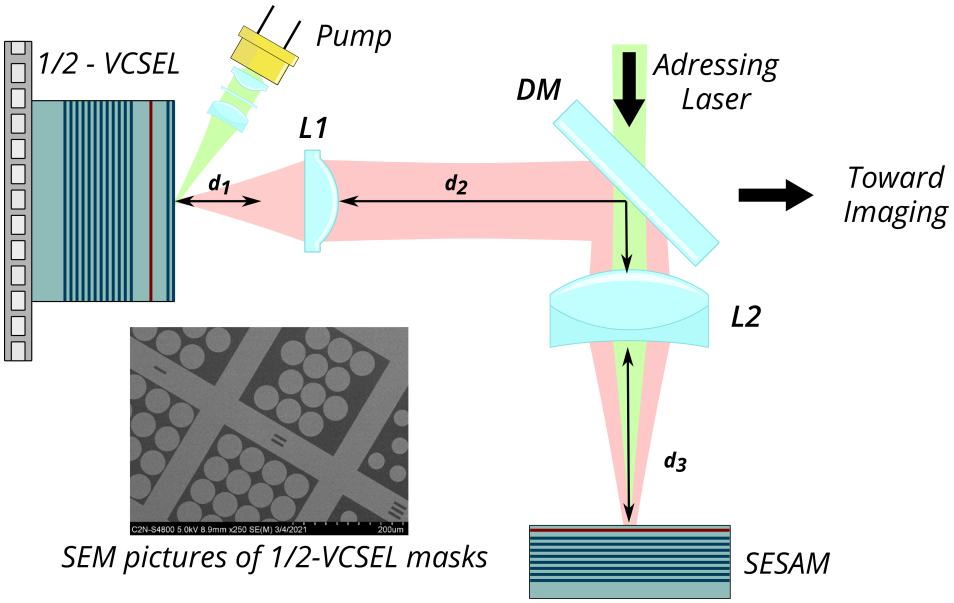


Figure 2. Experimental Set-up: cavity in $4-f$ configuration where $d_1 = f_1$, $d_2 = f_1 + f_2$ and $d_3 = f_2$. L1 is an optimized aspherical lense while L2 is an achromatic lense with $f_1 = 25mm$ & $f_2 = 50mm$. The 1/2 - VCSEL gain medium is optically pumped using one commercial 808 nm single mode laser diode at the brewster angle. A dichroic mirror (HR at $1064nm$) is used as an output coupler. A laser diode at 980 nm is used to locally pumped the SESAM. Insert). SEM image of some chromium mask processed on the 1/2-VCSEL.

We used a semiconductor gain mirror (1/2-VCSEL) and a semiconductor saturable absorber (SESAM) as mirror in a linear optical cavity (See fig. 2). The 1/2-VCSEL is based on GaAs III-V semiconductor materials for an emission at 1064 nm with an optical pumping scheme using a single mode diode laser at 808 nm. The pumping diode is place at the brewster angle to optimize transition into the device and obtain a circular gaussian pumped area of $50\mu m$ at $1/e^2$ radius. This device is used to generate the high gain necessary for laser operation while the optical pumping allow for a broad area utilisation useful for the generation of spatially localize state. The growth is done using MOVCD process. It is composed of a highly reflecting Bragg mirror and a MQWs active region. The QWs are distributed along the standing wave anti-nodes to ensure uniform carrier distribution. Post-processing has also been done to add a sub-wavelength non-diffractive 2D-patterned chromium mask. The

chromium high absorption allow to spatially control light structuration by modulation of losses (see insert of figure 2).

The SESAM is a device which introduces saturable losses generating optical bi-stable state critical for spatial localisation. It is based on GaAs platform with a highly reflecting ($> 99.9\%$) Bragg mirror, a large bandwidth and a slow lifetime compare to QW gain. An addressing laser diode at 980 nm with a size $5\mu m$ at $1/e^2$ in the SESAM can also be used to locally saturate the absorption.

The choice of a $4-f$ cavity design has been made in order to reach a self-imaging condition where the gain is image on the SESAM and reciprocally. An aspherical lens with an achromatic lens have been used to maximise the numerical aperture and minimize the total aberration. A dichroic mirror is used as an output coupler for the laser while allowing the use of an addressing laser. This set-up enables a high Fresnel number operation with weak diffraction while keeping the unsaturated losses low for high finesse cavity ($F \sim 100$). This configuration is equivalent to a plano-plano cavity at wavelength scale ranging from anomalous to normal diffraction regime. In this configuration a magnification of 2 is produce on the gain, in order to keep the saturation intensity ratio large, similarly as for passively mode-locked lasers.[8,9]

Using the output of the laser we image the plane of the gain onto a CCD camera to display the near field intensity of the laser emission. We also image the corresponding 2D intensity Fourier spectrum (Far Field) on another CCD camera in order to characterize the spatial field generated.

3. CLASSIFICATION OF THE SPATIAL STATES

This $4-f$ system can be characterised by three distinct spatial operations depending mainly on distance d_3. In figure 3 we show the three regimes where the top row show the intensity distribution of the near field on the gain and the bottom row it's corresponding 2D intensity Fourier spectrum (The red outline represents the numerical aperture limit of the system $NA_{max} = 0.2$). The laser was operating above the threshold.

The right column is taken with a large positive offset from the perfect self-imaging position of the SESAM representing a larger distance d_3. In this position we can observe an on axis gaussian emission with a $M^2 \simeq 1$. A perfect paraxial self-imaging system in a $4-f$ configuration should be marginally stable according to a simple ABCD matrix analysis[10] . However, the resulting pump heat load induced thermal profile, this system can be stable in normal diffraction. Indeed transverse temperature distribution will induce a refractive index profile resulting in a pump dependant focusing thermal lens[11] . This thermal lens will affect the resonator stability. In this case with a strong pumping power, we remain stable even for large diffraction value resulting in on-axis emission.

The center column shows a modulated near field intensity with a modulated on axis far field where the maximum angle in far field ($\theta = 0.067rad$) correspond to the modulation period in the near field ($T = 8\mu m$). In this case the distance d_3 is equal to the paraxial self-imaging condition meaning very low diffraction and spatial degeneracy of the transverse modes of the resonator. For very low diffraction, spherical aberrations (4th order diffraction) then becomes an important factor for on axis stability and limits the available numerical aperture of the system.

In the left column we can also see strong modulation on the near field but a ring on the far field and no emission on axes. This regime exhibits a strong conical wave component where laser emission propagate at an angle compare to previous regime. We call this regime the "Tilted-waves" because two spots on the Fourier spectrum create an interference pattern on the gain and the ring consists of a multiple spots with different azimuthal angles. We explain this behaviour by the fact that we are no longer stable on-axis because we are now in anomalous diffraction ($d_3 < f_2$) while for large incident angle lens spherical aberrations increases sufficiently to stabilise the system.

4. LIGHT STRUCTURATION

Concerning light structuration we are interested in the degenerate regime. On the left column of figure 4 we show the near field and Fourier spectrum of the system lasing on a difractiveless chromium mask, where the area delimited by the red outline correspond to lossless area. In this case we can see similar modulation as for figure 3

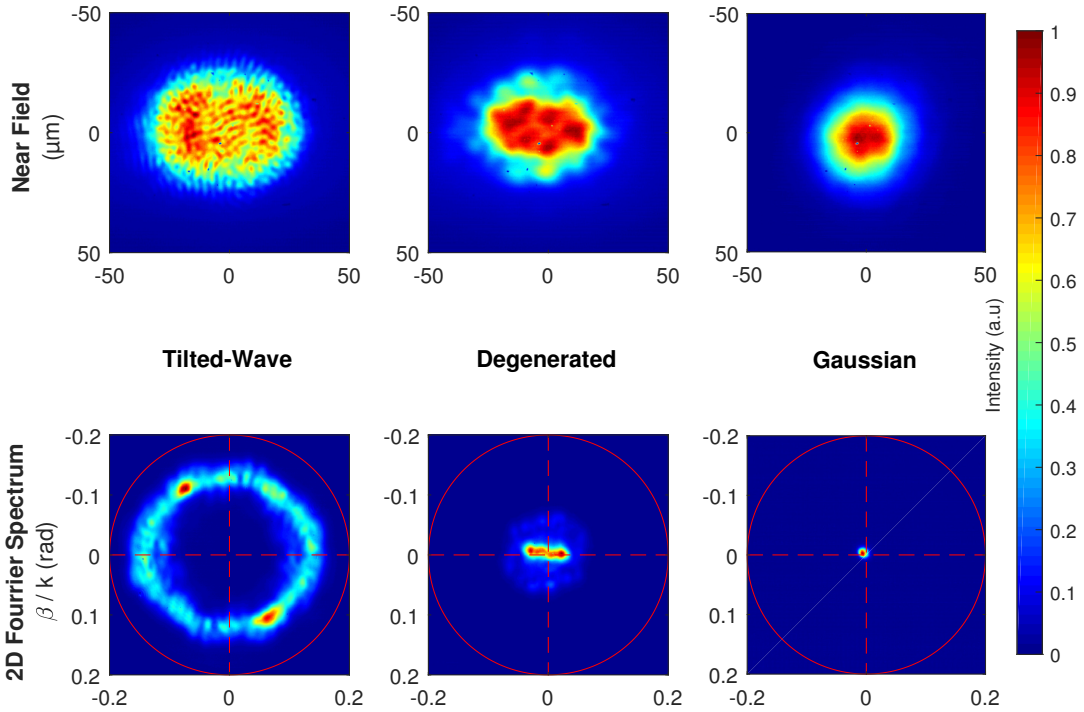


Figure 3. Top row). Near field intensity image of the gain plane depicting three different spatial operations. Bottom row). Corresponding 2D intensity Fourier spectrum (Red outline show the NA limit of the system, dotted line mark the $\beta = 0$ emission). Left). "Tilted-Wave" emission when $d_3 < f_2$. Center). Spatially degenerate emission at the self-imaging position when $d_3 = f_2$. Right). Normal diffraction regime with on-axis gaussian emission when $d_3 > f_2$. All these images are taken a the same pump power.

but the intensity in near field follows the aperture of the mask. This shows us that the system in self-imaging is capable of emitting any arbitrary complex wave shape.

The right column of figure 4 is taken for a pumping parameter bellow laser threshold, allowing a bi-stable spot coexisting with the off solution of the system. Furthermore, we see an offset from the centered emission in the 2D Fourier spectrum. This spot is also addressable from off state through a local saturation of the SESAM with the 980 nm injection seeding. This kind of result are strongly indicative of a non-linear structuration of the light where saturable absorption depth, diffraction, spherical aberration and self-guiding are essential parameters.

5. PERSPECTIVES

In conclusion we show the different regimes of operation for a VeCSEL in a self-imaging laser and his ability to structure light with an arbitrary wave using a sub-lambda chromium filtering mask. Current work is in progress to manage important physical parameter such as diffraction, aberration sign and the non-linearities strength. The goal being to achieve a large number (high dimensionality) of independently addressable localized structure. Other work is also focusing on the ability of the system to linearly multiplex several bi-stable laser spots. Another possible perspective is to combine spatially localized light with temporal localized structure to obtain dissipative light bullets in 3D.

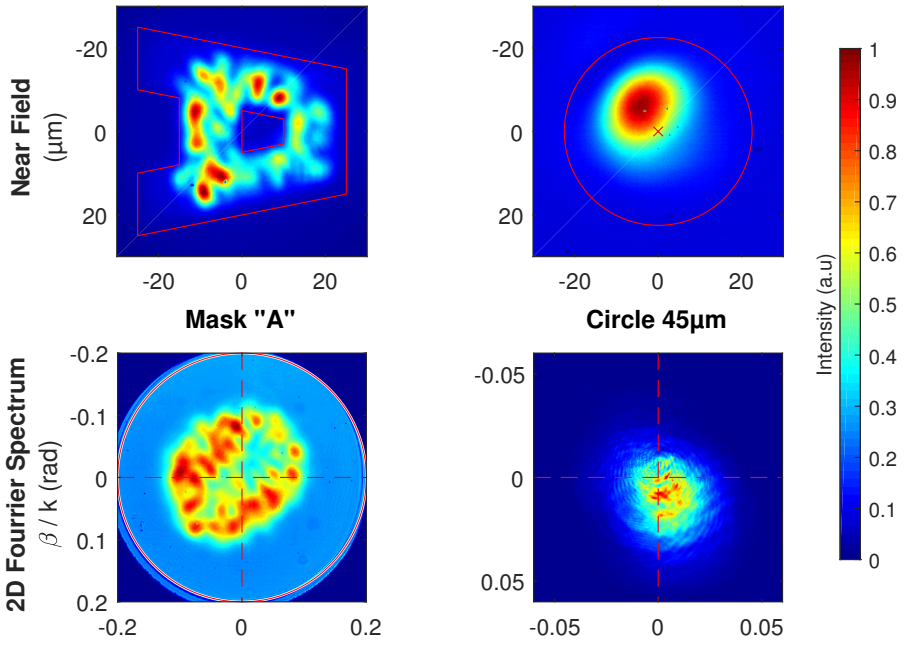


Figure 4. Top row). Near field intensity image of the gain plane depicting two different chromium masks (red outlines). Bottom row). Corresponding 2D intensity Fourier spectrum (Red outline show the NA limit of the system, dotted line mark the $\beta = 0$ emission). Left).Mask "A" of 50 μm height for pumping parameter $r > 1$. Right). Circular mask of 45 μm diameter emission for pumping parameter $r < 1$.

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REFERENCES

[1] Chesler, R. and Maydan, D., "Convex-Concave Resonators for TEM00 Operation of Solid-State Ion Lasers," *Journal of Applied Physics* **43**, 2254–2257 (May 1972).

[2] De Silvestri, S., Laporta, P., and Magni, V., "The role of the rod position in single-mode solid state laser resonators: Optimization of a cw mode-locked Nd:YAG laser," *Optics Communications* **57**, 339–344 (Apr. 1986).

[3] Hamel, P., Haddadi, S., Raineri, F., Monnier, P., Beaudoin, G., Sagnes, I., Levenson, A., and Yacomotti, A. M., "Spontaneous mirror-symmetry breaking in coupled photonic-crystal nanolasers," *Nature Photonics* **9**, 311–315 (May 2015).

[4] Khajavikhan, M., Simic, A., Katz, M., Lee, J. H., Slutsky, B., Mizrahi, A., Lomakin, V., and Fainman, Y., "Thresholdless nanoscale coaxial lasers," *Nature* **482**, 204–207 (Feb. 2012).

[5] Oulton, R. F., Sorger, V. J., Zentgraf, T., Ma, R.-M., Gladden, C., Dai, L., Bartal, G., and Zhang, X., "Plasmon lasers at deep subwavelength scale," *Nature* **461**, 629–632 (Oct. 2009).

[6] Barland, S., Tredicce, J. R., Brambilla, M., Lugiato, L. A., Balle, S., Giudici, M., Maggipinto, T., Spinelli, L., Tissoni, G., Knödl, T., Miller, M., and Jäger, R., "Cavity solitons as pixels in semiconductor microcavities," *Nature* **419**, 699–702 (Oct. 2002).

[7] Coullet, P., Riera, C., and Tresser, C., "A New Approach to Data Storage Using Localized Structures," *Chaos: An Interdisciplinary Journal of Nonlinear Science* **14**, 193–198 (2004).

[8] Keller, U., "2.1 Ultrafast solid-state lasers," in [*Laser Systems, Part 1*], Herziger, G., Weber, H., and Poprawe, R., eds., **11**, 33–167, Springer Berlin Heidelberg, Berlin, Heidelberg (2007).

[9] Paschotta, R. and Keller, U., "Passive mode locking with slow saturable absorbers," *Applied Physics B* **73**, 653–662 (Nov. 2001).

[10] Siegman, A. E., [*Lasers*], University Science Books (1986).

[11] Laurain, A., Myara, M., Beaudoin, G., Sagnes, I., and Garnache, A., "High power single–frequency continuously–tunable compact extended–cavity semiconductor laser," *Optics Express* **17**, 9503–9508 (June 2009).