Surface enhanced VCSEL for Sub-wavelength, long focal length with possible Airy beam generation

Outline of Presentation

- ➔ Introduction and Motivation
- ➔ Literature Survey
- ➔ Literature Summary
- ➔ Broad Objectives
- ➔ Problem Statement
- ➔ Required Hardware / Software details
- ➔ Methodology
- ➔ References

Introduction & Motivation

Introduction:

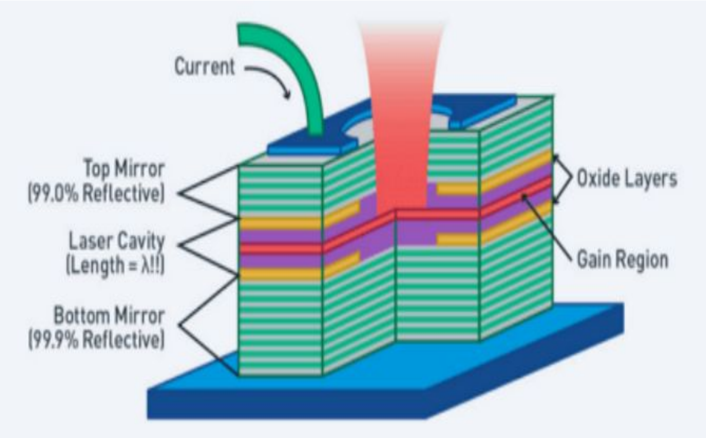
"Surface Enhanced VCSEL Laser for Sub-Wavelength, Long Focal Length with Possible Airy Beam Generation" explores integrating Vertical-Cavity Surface-Emitting Lasers (VCSELs) with advanced optical techniques to generate Airy beams. These beams, known for their non-diffracting, self-bending, and self-healing properties, hold potential for innovative photonic applications.

Motivation:

The demand for advanced laser technologies capable of operating at sub-wavelength scales with long focal lengths drives this project. Airy beams generated from VCSELs could revolutionize:

- Biomedical Imaging: Enhanced resolution and contrast for more accurate diagnostics.
- Optical Manipulation: Precise control for particle manipulation and trapping.
- Light-Sheet Microscopy: Non-invasive imaging with minimal damage to biological specimens.

This project aims to push the limits of current laser technologies, enabling more compact and versatile photonic devices.



Structure of a typical VCSEL

[1] K. T. Cook, "Design and Fabrication of VCSELs for 3D Sensing," UC Berkeley, 2019.

LITERATURE SURVEY

[1] H. T. Assafli, A. H. Abdulhadi, and W. Y. Nassir, "Design High Efficient Reflectivity of Distributed Bragg Reflectors," *Iraqi Journal of Laser, Part A*, vol. 15, pp. 13-18, 2016.

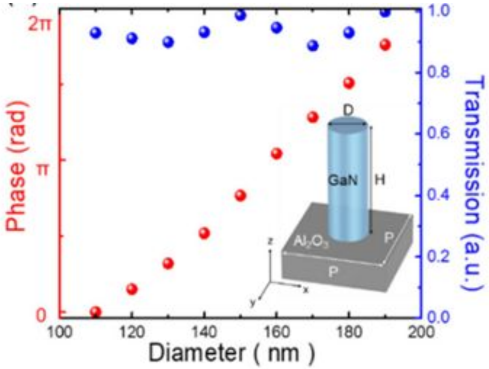
SECTION	IMPORTANT POINTS
Focus of paper	The study focuses on the design and characterization of Distributed Bragg Reflectors (DBRs) for optoelectronic applications, particularly at a wavelength of 2 µm. The paper investigates the effect of different materials, layer thicknesses, and alternating layer pairs on reflectivity
Key Findings	- DBR reflectivity can exceed 99% with the right choice of materials, layer thickness with number of alternating layers significantly affects reflectivity, more layers increasing reflectivity. - GaAs/AlAs and InAs/InSb achieved 99% reflectivity, making them ideal for VCSELs and other optoelectronic devices.
Experiment	Simulations were conducted using the Transfer Matrix Method (TMM) to analyze reflectivity for different DBR materials and study the impact of layer thickness and number of layers on performance.
Result	- GaAs/AlAs, InAs/InSb, and InSb/InP achieved 99% reflectivity with 20 layers. - GaAs/InAs had a lower reflectivity (73%), while GaSb/InSb only reached 37%, requiring more layers for higher performance. - Thinner DBRs are preferred to avoid carrier loss and excessive heating, making material selection crucial for optoelectronic applications.

[2] G. Porat, I. Dolev, O. Barlev, and A. Arie, “Airy beam laser,” *Opt. Lett.*, vol. 36, no. 20, pp. 4119–4121, 2011

SECTION	IMPORTANT POINTS
Focus of paper	Designing a laser that can emit an Airy beam, a specific type of optical beam with unique properties like curved trajectory, low diffraction, and self-healing capabilities. The goal is to create a compact method for generating Airy beams directly from a laser using high contrast grating that modulates phase and amplitude.
Key Findings	**Airy Beam Generation**: By using a grating with a cubic phase modulation as the laser's output mirror, the experiment successfully generated a two-dimensional Airy beam. **Self-Healing Property**: The Airy beam maintained its shape even after encountering obstacles, which was demonstrated by partially blocking the beam and observing its recovery over distance. **Power Characterization**: The laser’s output power increased linearly with the pump power, achieving a maximum output power of 67.5 mW.
Result	The experimental Airy beam profile showed good alignment with theoretical predictions. This can be used to generate other complex beam profiles, like holograms, making it versatile for various optical applications.

[3] H. Y. Kuo *et al.*, “Cubic-phase metasurface for three-dimensional optical manipulation,” *Nanomaterials (Basel)*, vol. 11, no. 7, p. 1730, 2021.

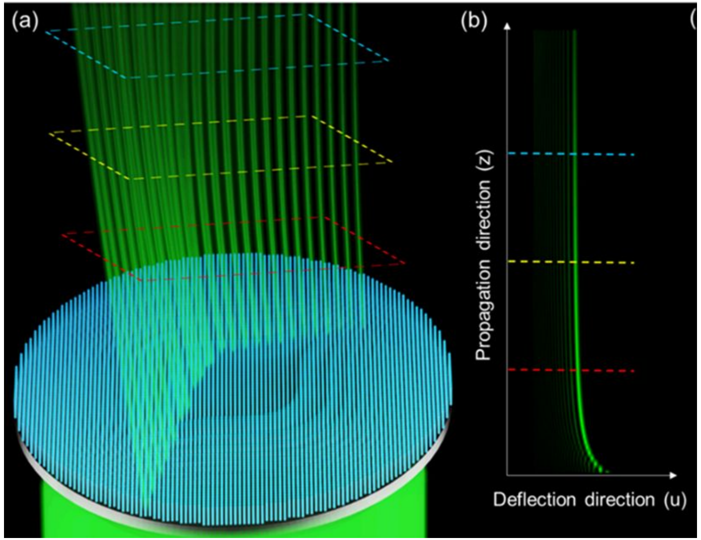
SECTION	IMPORTANT POINTS
Focus of the Paper	Design of a cubic-phase metasurface, composed of GaN circular nanopillars to generate a vertically accelerated two-dimensional Airy beam in the visible region with the Phase profile $\phi(x,y) = \frac{k_0(x^3+y^3)}{12a}$
Key Findings	The study utilized a wavelength of 532 nm for the generation of the vertically accelerated 2D Airy beam. The GaN circular nanopillars that compose the cubic-phase metasurface had diameters ranging from 110 nm to 190 nm, with a height of 800 nm. The propagation characteristics of the generated Airy beam exhibit unique features such as non-diffraction, self-acceleration, and self-healing, which were experimentally verified. The optical manipulation system utilizing the cubic-phase metasurface demonstrated effective trapping and guiding of microspheres in both lateral and axial directions, showcasing the potential for 3D manipulation



[3] H. Y. Kuo *et al.*, “Cubic-phase metasurface for three-dimensional optical manipulation,” *Nanomaterials (Basel)*, vol. 11, no. 7, p. 1730, 2021.

[3] H. Y. Kuo *et al.*, “Cubic-phase metasurface for three-dimensional optical manipulation,” *Nanomaterials (Basel)*, vol. no. 7, p. 1730, 2021.

SECTION	IMPORTANT POINTS
Result	Successfully generated vertically accelerated 2D Airy beams. Validated beam's propagation characteristics and trajectory.



[3] H. Y. Kuo *et al.*, “Cubic-phase metasurface for three-dimensional optical manipulation,” *Nanomaterials (Basel)*, vol. 11, no. 7, p. 1730, 2021.

Propagation characteristics of a vertically accelerated 2D Airy beam.

(a) Schematic diagram of generating a vertically accelerated 2D Airy beam by an all-dielectric cubic-phase metasurface.
(b) Numerically calculated beam trajectory of a vertically accelerated 2D Airy beam

[4] K. T. Cook, “Design and Fabrication of VCSELs for 3D Sensing,” UC Berkeley, 2019.

SECTION	IMPORTANT POINTS
Focus of paper	This paper includes some basic knowledge of VCSEL and improvements for usage in multiple systems for 3D sensing.
Key Findings Why VCSEL?	• Inability of Edge Emitting Laser (EEL) in chip detection. • Non circular output light spot. • Oxide layer is designed to shape the output beam spot light circularly symmetrical, , making VCSEL lasers easier to be coupled with optical fibre. • Implementing array lasers. Arrays of VCSELs can be produced with the same process by replicating the unit cell of a single VCSEL across a chip where multiple emitters can be integrated side by side.
Experiment	• **Initial 100-Emitter Arrays**: The author successfully demonstrated initial VCSEL arrays with up to 100 emitters, achieving a wall plug efficiency of more than 20%.
Result	• A wall plug efficiency of over 35%(highest recorded).

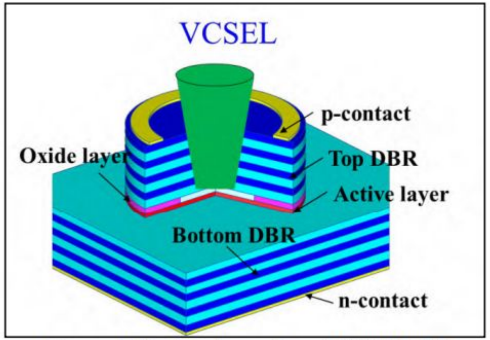


Figure 1. Basic schematics of VCSEL [1]

[1] K. T. Cook, “Design and Fabrication of VCSELs for 3D Sensing,” UC Berkeley, 2019.

[5] P. Goyal, S. Gupta, G. Kaur, and B. K. Kaushik, "Performance analysis of VCSEL using finite difference time domain method," *Optik (Stuttg.)*, vol. 156, pp. 505–513, 2018.

SECTION	IMPORTANT POINTS
Focus of paper	The paper focuses on analyzing the performance of a VCSEL using the Finite Difference Time Domain (FDTD) method. The goal is to achieve simulations for VCSEL behavior over a wavelength range of 1310-1350 nm for short range optical applications.
Key Findings	The VCSEL structure included both DBR mirrors and an active region for laser light generation. GaAs substrate. Al0.12Ga0.88As/GaAs upper and lower DBR.
Result	The maximum power of 0.81 W is obtained at a wavelength of 1320 nm

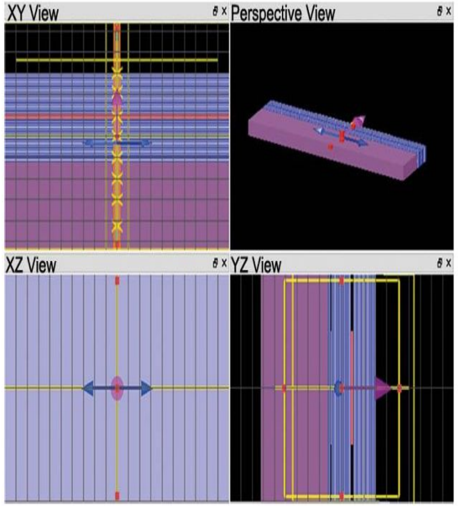
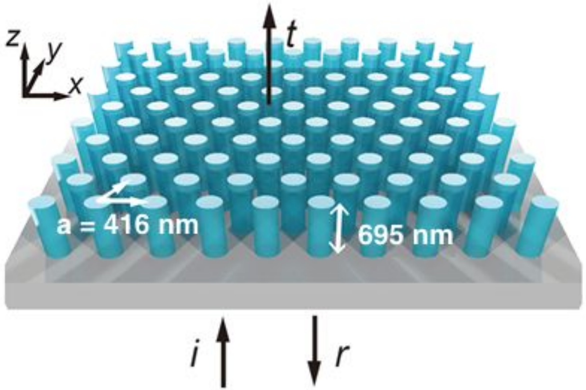


Figure 1. XY, Perspective, XZ and YZ view of VCSEL model at 1310 nm using FDTD Lumerical software

[4] P. Goyal, S. Gupta, G. Kaur, and B. K. Kaushik, "Performance analysis of VCSEL using finite difference time domain method," *Optik (Stuttg.)*, vol. 156, pp. 505–513, 2018.

[6] Z.-B. Fan *et al.*, "Silicon Nitride Metalenses for Close-to-One Numerical Aperture and Wide-Angle Visible Imaging," *Phys. Rev. Applied*, vol. 10, no. 1, p. 014005, Jul. 2018

SECTION	IMPORTANT POINTS
Focus of paper	Design of high numerical aperture (NA) silicon nitride (SiN) metalenses for close-to-one NA and wide-angle visible imaging.
Key Findings	**Sub-Wavelength Focusing:** SiN metasurfaces enable high-NA, sub-wavelength focusing, enhancing VCSEL beam control. **Long Focal Length Metalens:** The centimeter-scale SiN metalens supports extended focal lengths, essential for collimated laser applications. **Airy Beam Potential:** The phase modulation capability suggests feasibility in generating structured beams like Airy beams. **High Transmission & CMOS Compatibility:** ~80% transmission across visible wavelengths allows seamless integration with VCSELs. **Hexagonal Nanopillar Lattice:** Enables precise beam shaping beyond Gaussian profiles.
Result	The obtained wavelengths in the results ranged from **480 nm to 580 nm**, with the designed wavelength being **633 nm**. The metalens demonstrated sub-wavelength focusing **NA~0.98**

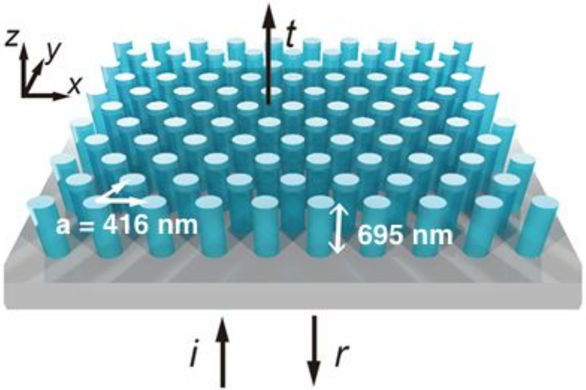


[6] Schematic of the grating constructed by a low-refractive-index SiN array with circular nanopillars on a fused silica substrate

[6] Z.-B. Fan *et al.*, “Silicon Nitride Metalenses for Close-to-One Numerical Aperture and Wide-Angle Visible Imaging,” *Phys. Rev. Applied*, vol. 10, no. 1, p. 014005, Jul. 2018

Design Parameters

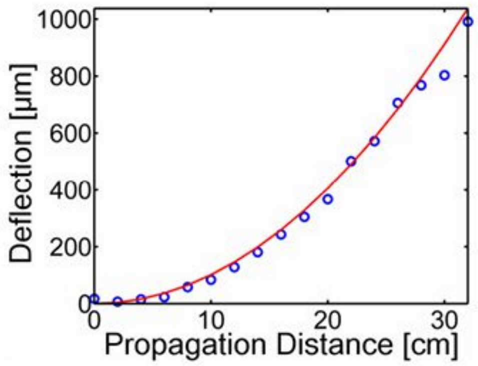
Parameter	Value
Material	Silicon Nitride (SiN)
Height	695 nm
Nanopillar Diameter	170 – 374 nm
Minimum Spacing	42nm
Transmission Efficiency	~80%
Wavelength	633 nm (Visible: 480-780 nm)



[6] Schematic of the grating constructed by a low-refractive-index SiN array with circular nanopillars on a fused silica substrate

[7] G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, “Observation of accelerating Airy beams,” *Phys. Rev. Lett.*, vol. 99, no. 21, p. 213901, 2017.

SECTION	IMPORTANT POINTS
Focus of paper	The authors aim to derive the self-accelerating property of Airy beams by solving the paraxial diffraction equation and demonstrating that their intensity maxima follow parabolic trajectories.
Key Findings	1) **Mathematical Derivation**: The authors solve the paraxial diffraction equation (analogous to the Schrödinger equation) to show that Airy wave packets exhibit self-acceleration with the eqn: $\mathbf{S}_{\mathbf{peak}} = \frac{\xi^2}{4}$ 2) the main intensity lobe of the Airy beam follows a parabolic trajectory, confirming self-acceleration even in the absence of external forces. 3) **Experimental Verification**: Using spatial light modulators and Fourier optics, they generate 1D and 2D Airy beams, confirming that their intensity maxima accelerate transversely while the overall wave packet remains diffraction-resistant.
Result	The authors proved that Airy beams naturally bend as they travel without any external force and derived a mathematical expression proving this self-acceleration and confirmed it through experiments.



[7] G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, “Observation of accelerating Airy beams,” *Phys. Rev. Lett.*, vol. 99, no. 21, p. 213901, 2007.

[8] J. Broky, G. A. Siviloglou, A. Dogariu, and D. N. Christodoulides, “Self-healing properties of optical Airy beams,” CREOL/College of Optics & Photonics, Univ. of Central Florida, 2018.

SECTION	IMPORTANT POINTS
Focus of paper	The research investigates the self-healing property of the optical airy beam through the use of mathematical techniques and experimental confirmations. The research explores how these beams reconstruct themselves following collisions with obstacles.
Key Findings	1) **Self-Healing from the Paraxial Wave Equation**: The normalized paraxial diffraction equation is used to describe airy beam evolution.The airy beam solution shows how it preserves its form while bending and self-reconstructing after obstacles. $\phi(x,z) = Ai\left(x - \frac{z^2}{4}\right) exp\left[a\left(x - \frac{z^2}{4}\right)\right]$, Airy Function: $Ai(x) = \frac{1}{\pi}\int_0^\infty \cos\left(\frac{t^3}{3} + xt\right) \mathrm{d}t$ 2) **Power Flow**: The poynting vector describes energy flow within the beam. The transverse component is the one that redistributes energy, allowing for self-healing. 3) **Trajectory and Acceleration:** The airy beam self-bending path is parabolic. This acceleration aids the beam in overcoming obstacles and rebuilding further down its propagation route.
Result	The equations that were derived anticipate that Airy beams don't diffract and are able to reconstruct when blocked. The transverse power flow in the Airy function solution explains why energy redistributes to recover the original beam shape. Simulations and experiments validate that Airy beams self-heal.

LITERATURE SUMMARY

SL NO	NAME OF PAPER	SUMMARY	KEY TAKEAWAY
[1]	**K. T. Cook, “Design and Fabrication of VCSELs for 3D Sensing,” UC Berkeley, 2019.**	Outlines the significance of VCSELs in several optical systems, such as, for instance, data transmission in large-scale data centers and supercomputers and, last but not least, cutting-edge applications, like autonomous vehicles, medical imaging, facial recognition, and gesture detection.	●Tunable VCSEL Design: The dissertation demonstrates an innovative design to scale the fractional tuning range in the tunable VCSEL. ●High-Power VCSEL Arrays: development of high-power, high-efficiency VCSEL arrays to illuminate larger areas for gesture and facial recognition applications.
[2]	**M. C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, “A surface-emitting laser incorporating a high-index-contrast subwavelength grating,” *Nat. Photonics*, vol. 1, no. 2, pp. 119–122, 2007.**	This paper emphasises on how the HCG provides both efficient optical feedback and control of the wavelength and polarization of the emitted light. Such integration reduces the required VCSEL mirror epitaxial thickness by a factor of two and increases fabrication tolerance	●35–40 pairs of GaAs–AlGaAs DBRs approximately 5 mm in thickness can be replaced by a 0.235 mm thick AlGaAs-based HCG with an equivalent reflectivity. ●The wavelength scalability and versatility of the single-layer HCG design could provide numerous benefits when fabricating surface-normal optoelectronic devices, such as high-brightness LEDs, photovoltaic cells, optical filters and detectorS for a wide range of wavelengths.

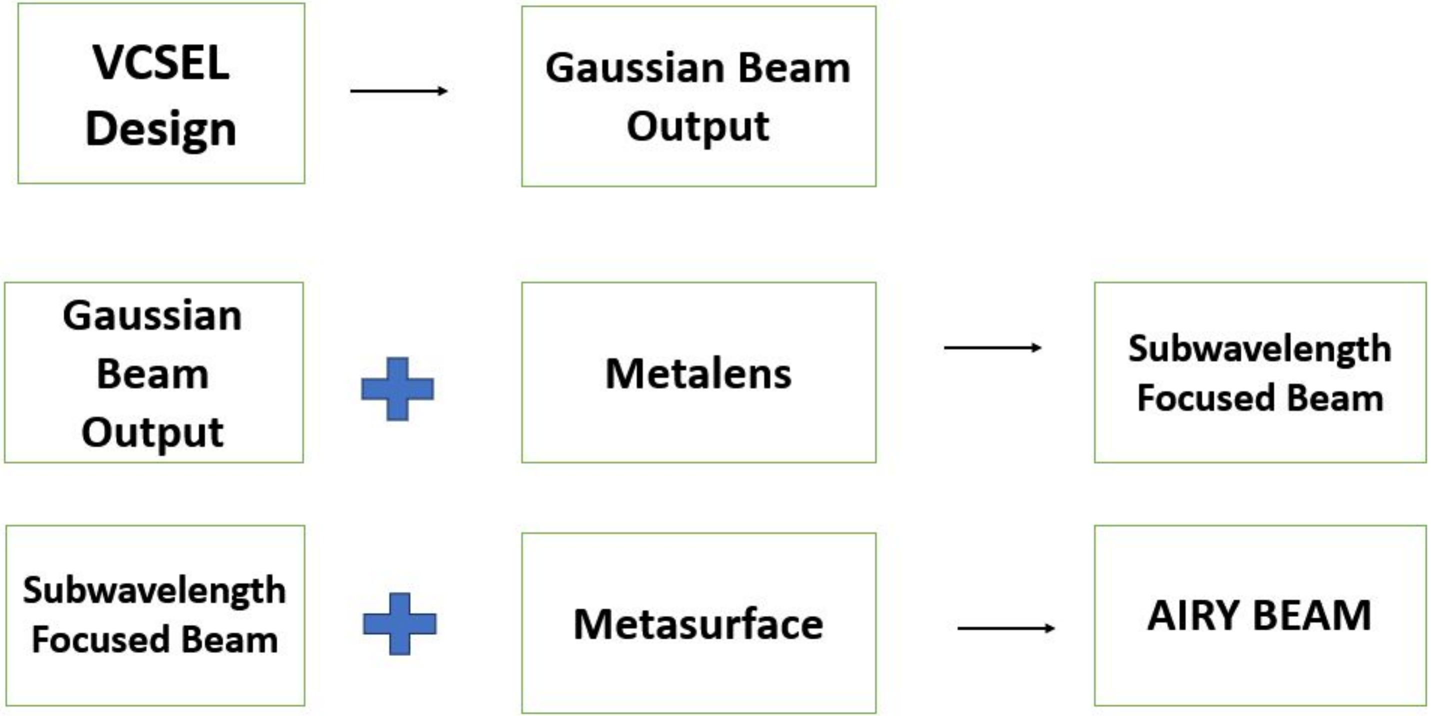
[3]	**H. Y. Kuo *et al.*, "Cubic-phase metasurface for three-dimensional optical manipulation," *Nanomaterials (Basel)*, vol. 11, no. 7, p. 1730, 2021.**	• A cubic-phase dielectric metasurface, using GaN nanopillars, generates vertically accelerated 2D Airy beams with self-healing and non-diffraction properties. • Offers a compact, polarization-independent alternative to bulky SLM for 3D optical particle control.	• The metasurface simplifies optical manipulation systems, making them more compact and versatile. • Self-healing and low-diffraction properties of Airy beams enhance their utility in non-contact particle manipulation.
[4]	**G. Porat, I. Dolev, O. Barlev, and A. Arie, "Airy beam laser," *Opt. Lett.*, vol. 36, no. 20, pp. 4119–4121, 2011**	• Features include curved trajectory, low diffraction, and self-healing, achieved via cubic phase modulation and Fourier transform. • Airy beams are generated using a diffraction grating as an output mirror. A solid-state laser produced a 2D Airy beam with properties matching theory, including self-healing and efficient power output.	• The integration of Airy beam generation directly within the laser cavity simplifies the system, enhancing practicality. • Self-healing property of Airy beams has potential applications in fields like optical trapping, plasma waveguiding, and robust communication systems.
[5]	**P. Goyal, S. Gupta, G. Kaur, and B. K. Kaushik, "Performance analysis of VCSEL using finite difference time domain method," *Optik (Stuttg.)*, vol. 156, pp. 505–513, 2018.**	• 2D model simulation of vcsel using FDTD. • The state of art is given • The laser is designed to work at 1320 nm	• The State of art which gives us the dimensions of Active layer and Bragg reflectors • The position of source and the position of monitors

[6]	**Kyoko Kitamura, Kyosuke Sakai, and Susumu Noda, "Sub-wavelength focal spot with long depth of focus generated by radially polarized, narrow-width annular beam," Opt. Express 18, 4518-4525 (2010)**	● Measured intensity profiles for original (δ=0.0) and modified (δ=0.8) beams. ● Original beam (δ=0.0) shows single to double peak shift, intensity drops at ±1 μm, highly dispersed at ±2 μm. ● Modified beam (δ=0.8) maintains single peak profile across z=−2 to 2 μm. ● Modified beam (δ=0.8) produces smaller spot (600 nm) vs. original beam (1200 nm).	● **Improved depth of focus** with δ=0.8. ● **Smaller focal spot** with modified beam. ● **Better performance** for high-precision applications.
[7]	**I.-S. Chung, J. Mork, P. Gilet, and A. Chelnokov, "Subwavelength grating-mirror VCSEL with a thin oxide gap," IEEE Photonics Technol. Lett., vol. 20, no. 2, pp. 105–107, 2008.**	●New VCSEL structure based on a subwavelength grating mirror and a thin oxide gap. ●The thin oxide gap can replace the air gap with similar reflectivity. The laser can keep its output focused in a single mode. Oxide gap HCG shows a high reflectivity of ~95%.	●Simplification of VCSEL fabrication, improve mechanical stability, enhance single-mode and polarization stability by replacing the air-gap HCG with a thin oxide gap. ●The oxide gap HCG VCSEL exhibited similar performance , with enhanced mechanical stability and simpler fabrication. 25 dB polarization suppression ratio 0.9 mW output power.
[8]	**B. Yalizay, B. Soylu, and S. Akturk, "Optical element for generation of accelerating Airy beams," J. Opt. Soc. Am. A Opt. Image Sci. Vis., vol. 27, no. 10, pp. 2344–2346, 2010.**	The paper presents an affordable optical element to generate accelerating Airy beams—light beams that curve along a parabolic path. Traditional Airy beam setups are complex, but this design uses **standard** cylindrical lenses to achieve the necessary cubic phase profile.	●By combining plano-convex and plano-concave cylindrical lenses, obtained cubic phase profile required for Airy beams. ●**Simplified Process**: This design eliminates the need for complex modulators or specialized materials, using a simple setup to transform a Gaussian beam into an Airy beam that follows a curved path

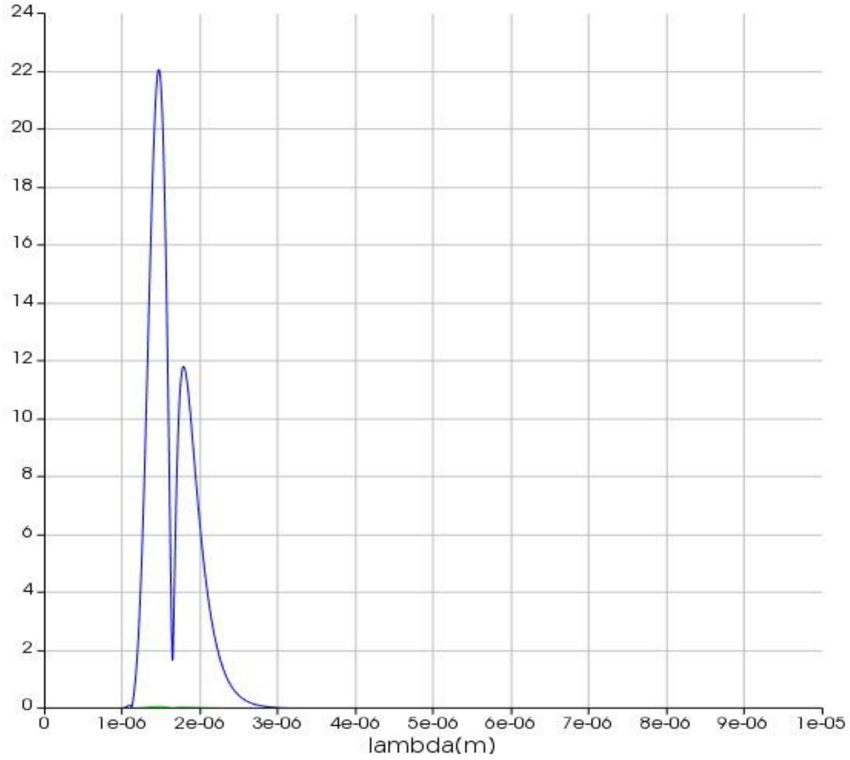
[9]	**N. Voloch-Bloch, Y. Lereah, Y. Lilach, A. Gover, and A. Arie, “Generation of electron Airy beams,” Nature, vol. 494, no. 7437, pp. 331–335, 2013.**	Discusses the experimental generation of Airy beams using free electrons, focusing on their non-diffracting and self-healing properties. The study aims to create electron wave packets that maintain shape while following parabolic trajectories	•The electron Airy beams exhibited non-spreading characteristics and self-restoration after encountering obstacles, highlighting their unique propagation dynamics. •Results indicate potential uses in quantum optics, electron microscopy, and materials science, where precise electron trajectory control is crucial
[10]	**Y.-Q. Cao, “Development of vertical cavity surface emitting laser modulation for data communication,” 2020, vol. 1653.**	•High-Power VCSEL Arrays: A novel fabrication technique using selective oxidation of AlGaAs creates HCG reflectors within VCSEL arrays, reducing costs and improving performance for gesture and facial recognition. •Can be tested at the wafer level. This allows VCSEL wafers and even individual devices to be binned for different applications, reducing the overall cost of a VCSEL •Small size, easy integration into high-density two-dimensional array.	•VCSELs are capable of high-speed data transmission, achieving up to 100 Gbps in a single lane using PAM4. Additionally, an energy efficiency of 50 fJ/bit was reported at room temperature. They also demonstrated reliability under high-temperature conditions, with the ability to operate at 90° C while maintaining high data rates.

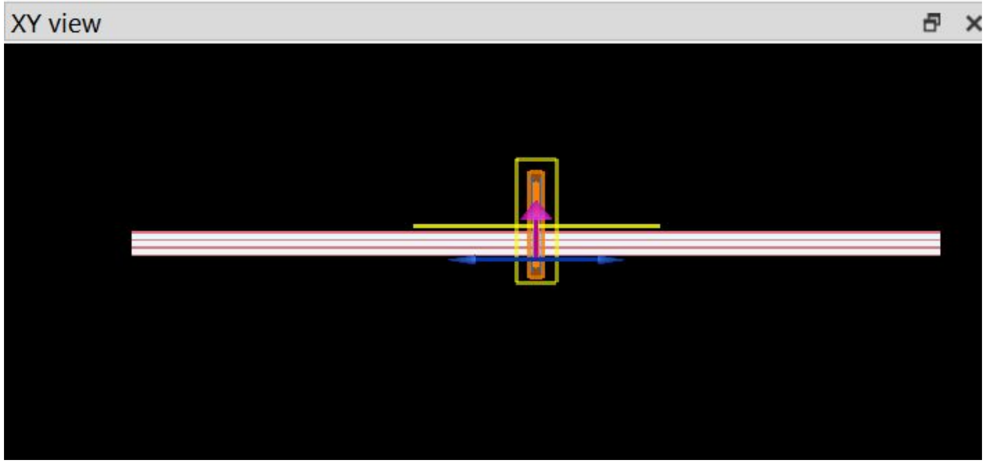
METHODOLOGY

BLOCK DIAGRAM



Implementation-DBR



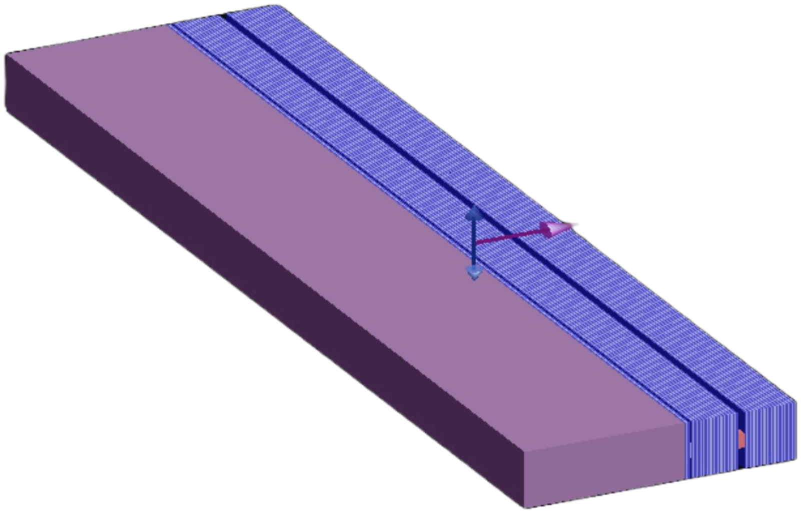


This is the wavelength vs amplitude graph.
Here dip is observed at 1.55um

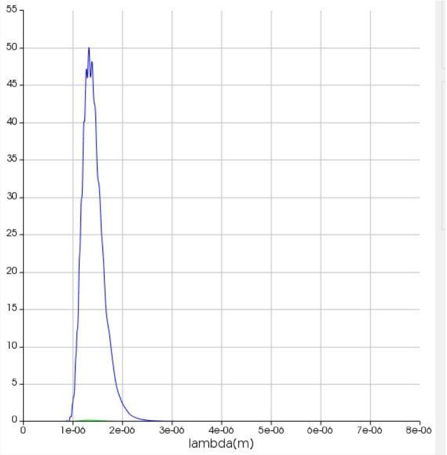
ah = 0.111µm , nh = 3.5
al = 0.267µm , nl = 1.45
Wavelength = 1.55µm

Implementation - VCSEL

Parameters	Values
Substrate Material	GaAs
Substrate Material Refractive Index	3.5227
Lower DBR Material	AlAs/GaAs
Lower DBR Material Refractive Index	2.9/3.5227
Lower DBR Thickness	Thickness1=0.1139μm Thickness2=0.0983μm
Lower DBR Layers	30
Active Region Material	Five compressively strained $In_{0.21}Ga_{0.79}AsP$ Quantum Wells (QWs) with tensile-strained $In_{0.21}Ga_{0.79}AsP$ barrier layers
Upper DBR Material	$Al_{0.12}Ga_{0.88}As/GaAs$
Upper DBR Material Refractive Index	3.66/3.5227
Upper DBR Thickness	Thickness1=0.1082μm Thickness2=0.0983μm
Upper DBR Layers	30
Wavelength Range	1310nm-1350nm



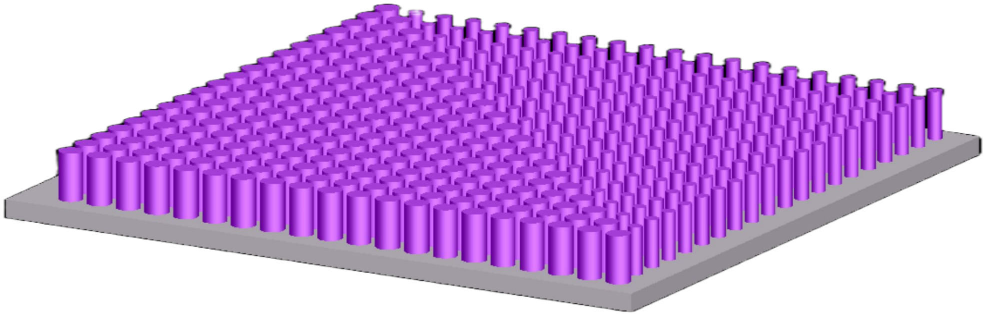
Design of VCSEL in FDTD



Implementation - Metasurface

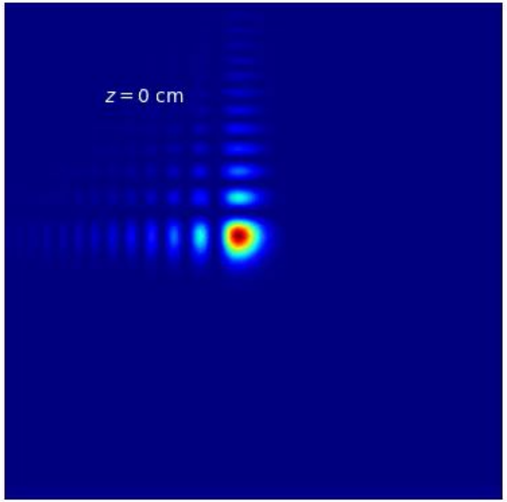
Nanopillar Material: GaN (Gallium Nitride)
Substrate Material: Al_2O_3 (Sapphire)

Parameters	Value
Number of Nanopillars	20 × 20 (or scalable to 40 × 40)
Nanopillar Height	800nm
Nanopillar Spacing (Pitch)	250nm
Diameter Range	110nm - 190nm

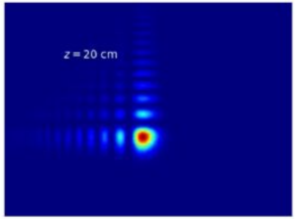


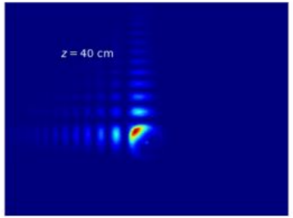
Design of a 20×20 array of GaN nanopillars on an Al_2O_3 substrate in FDTD to impart a cubic phase profile for Airy beam generation through spatially varying phase shifts.

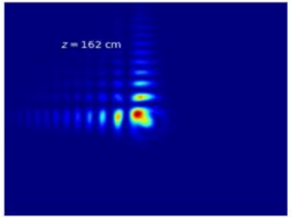
AIRY BEAM PROPAGATION

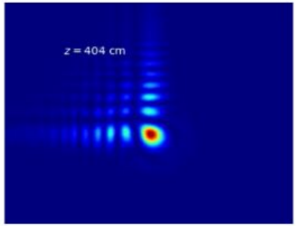


Implementation- Self Healing









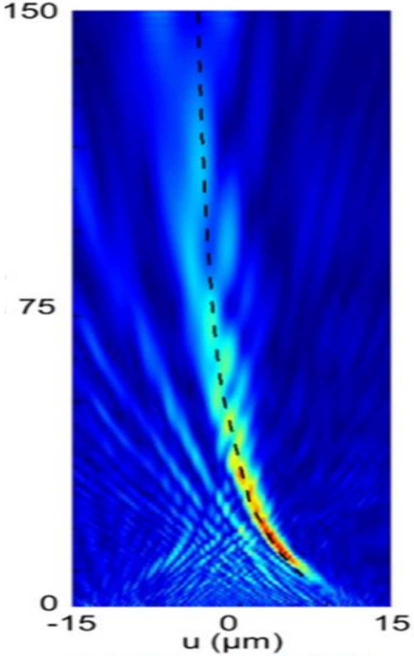
To show self healing property of airy beam:
Obstruction at 40cm.

Result:
Beam reconstructs it shape.
Follows the same path and propagates.

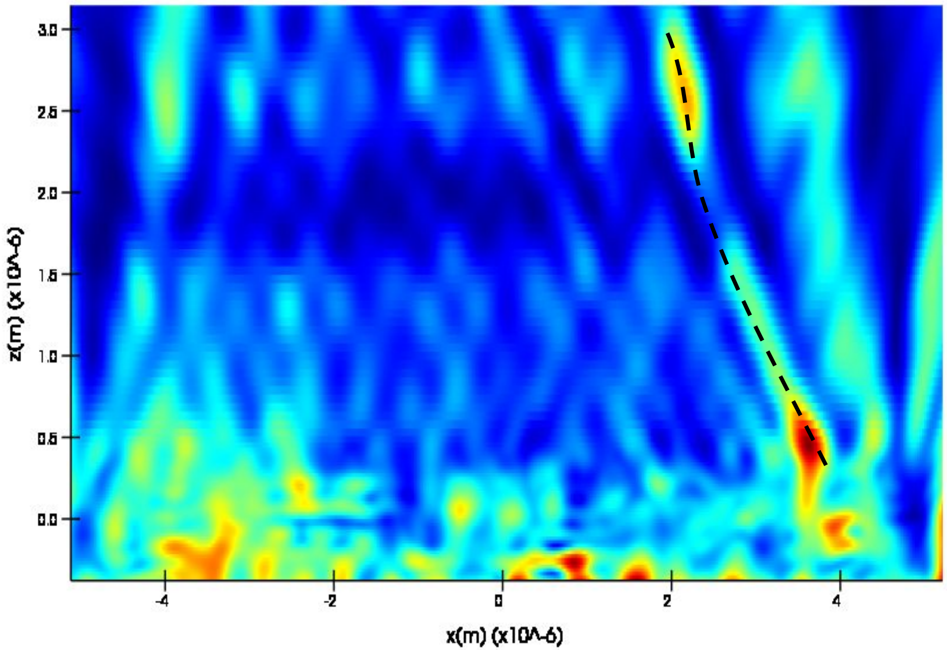
The link to video: https://drive.google.com/file/d/10cW0TsSZHicWYcK_IxyEaw6RuV1kTUwq/view?usp=sharing

Results

Comparative Study



[3] H. Y. Kuo *et al.*, “Cubic-phase metasurface for three-dimensional optical manipulation,” *Nanomaterials (Basel)*, vol. 11, no. 7, p. 1730, 2021.



FDTD simulated Electric Field distribution profile of the GaN metasurface with a cubic phase along the optical axis at the operating wavelength of 532 nm

OBJECTIVES

Gap	Current Challenge	Objective	Goal
Traditional VCSELs produce Gaussian beams, not Airy beams, without additional optics.	Designing a VCSEL structure that generates an Airy beam requires precise phase modulation.	Design and simulate a VCSEL with DBRs. Further integrate a metalens for sub-wavelength focusing.	Use FDTD simulations to test the relationship between amplitude and wavelength.
Achieving and analyzing Airy beam characteristics (subwavelength focus, self-bending).	Modeling and mathematical proof of the Airy beam properties accurately within software and confirming subwavelength focusing and self-healing.	Study and confirm the Airy beam profile features through simulations and mathematical calculations, ensuring sub-wavelength focusing is achieved.	Measure key beam characteristics (curved trajectory, self-healing, and sub-wavelength focus) in FDTD, ensuring the beam meets theoretical Airy properties.
The metasurface can shape beams in unique ways but need careful adjustments.	Finding the right grating size, metalens design, and pattern to achieve sub-wavelength focusing while maintaining a strong beam and correct phase shaping into an Airy beam.	Adjust the gratings, metalens, and cubic phase modulation design to create the right beam shape while achieving sub-wavelength focus.	Ensure appropriate orientation of the VCSEL, metalens, and cubic phase metasurface to produce an Airy beam with sub-wavelength focus.

PROBLEM STATEMENT

Design and optimization of a VCSEL-based system integrated with a metalens and metasurface to achieve sub-wavelength focusing and generate an Airy beam with controlled phase modulation using software FDTD Lumerical.

Software

- LUMERICAL (Finite Difference Time Domain)
- Python

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THANK YOU