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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The overall program objective is to develop an on-chip UV μ-laser that is able to excite fluorescence from bio-aerosols. This objective requires that we design μ-lasers that have low threshold with directionality in their emission. Hence, there is a need to optimize the pumping geometry of the μ-disk and the shape for maximum output efficiency. The resulting non-circular shapes necessitated that we understand some principles of chaos theory.

15. SUBJECT TERMS

GaNμ pillars, polymer micro-structures, on-chip UV μ laser, refractive escape

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P-N JUNCTION DIODE ULTRA-VIOLET LASERS WITH DIRECTIONAL EMISSION FROM NON-CIRCULAR OPTICAL CAVITIES FOR BIO SENSING

INTERIM REPORT

RICHARD K. CHANG

15-MAR-2000 – 29-JUN-2001

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

F49620-00-1-0182

YALE UNIVERSITY

1) Overall Program Objective:

The overall program objective is to develop an on-chip UV μ-laser that is able to excite fluorescence from bio-aerosols. This objective requires that we design μ-lasers that have low threshold with directionality in their emission. Hence, there is a need to optimize the pumping geometry of the μ-disk and the shape for maximum output efficiency. The resulting non-circular shapes necessitated that we understand some principles of chaos theory.

2) Progress

GaN μ-pillars (2 μm tall) of various shapes and sizes were made. In order to investigate the shapes that would produce directionality in the laser emission with maximum output efficiency from a μ-pillar laser, we designed a mask consisting of various shapes (ellipses, quadrupoles, dodeca-hexapoles, square, triangles, pentagons, hexagons, and several irregularly shaped micro-structures). This mask was then used in a standard photolithography process followed by CARIBE etching process in order to produce a 2 μm-high GaN μ-pillar, with a mirror finish for both the top face and the side wall. Unlike the case with reactive-ion etching that produces a roughened surface, the CARIBE etching process produced a smooth surface. Nevertheless, the CARIBE process caused the 2 μm pillar to taper slightly (smaller at the top and larger toward the bottom). Dr. Michael Knessel from PARC-Xerox was kind enough to do the photolithography and CARIBE process for us. For pillars with cross-sectional shape of an ellipse or a quadrupole, the distortion amplitude ε was varied from $\varepsilon = 0$ (a circle) to $\varepsilon = 0.20$ with steps of $\Delta\varepsilon = 0.02$.

The imaging technique, which we introduced, was used to measure simultaneously the far-field intensity and the sidewall image. This technique provided us with information as to where the light was exiting from the side wall of the micro-structure which was lasing as a result of optically pumping the top face. The sidewall image was measured every 5° intervals relative to a particular high-symmetry axis. A composite of the image data taken at every 5° provided a 2-d map that contained information about the far-field intensity versus external angle and the spatial location where light emerged along the sidewall

Such 2-d maps were measured for every micro-structure we designed for the mask. Some of the 2-d data is being compared to results deduced from chaos theory which accounts for refractive escape of the radiation (treated as billiards or as waves) from the cavity. Refractive escape occurs when the internal rays have an incident angle that is less than critical angle(θ_c) for total internal reflection. The external angle of this refractive-escaped ray obeys Snell's Law of refraction. The output coupling efficiency of a refractive-escaped ray is several orders of magnitude larger than that of a tunneling or diffraction-escaped ray, which has the internal incident angle greater than θ_c.

Identical micro-structures of PMMA polymers were made. Because the ray-dynamics results are sensitive to the index of refraction of the micro-structure, it is desirable to make the **same** micro-structure shape of GaN and another material, such as PMMA polymer which has a significantly different index of refraction from that of GaN ($n = 2.65$ for GaN and $n = 1.49$ for PMMA polymers). Professor Joseph Zyss of Ecole Normale Supeieur of Cachen is collaborating with us and has made polymer micro-structures according to the two masks that we sent, one was the mask for the GaN micro-structures and other specially designed mask consisting of hundreds of micro-structures of interest to telecommunication. These polymer micro-structures contained a lasing dye (coumarin), enabling us to study the lasing and non-lasing characteristics of various micro-structures

3) Significant Accomplishments

I) All the GaN pillars with ellipse, circular, quadrupolar, and dodeca-hexapolar micro-pillars have been measured The data are plotted in the 2-d map format and/or polar plots format for the far field(directionality of the lasing emission) and the image field (where the laser radiation is emerging from the sidewall).

II) Similar measurements and displays as above have been done for PMMA micro-structures containing coumarin laser dyes. The GaN and polymer lasing emission results form an interesting comparison, because of the big difference in the index of refraction.

III) The mode characteristics of a square-shaped μ-pillar is of potential interest to add/drop filters need for DWDM, Several tyoes of experiments were initiated in order to test the value of "mode counting" scheme in reciprocal space, $k_x = 2\pi m_x./\lambda$.and $k_y = 2\pi m_y./\lambda$ for the 4-bounce rays within a square-shaped cavity. We measured the elastic scattering spectra from a fiber with a square-shaped cross-section. Within the free-spectral-range (FSR) there existed three to four modes, consistent with the presence of the off-axis transverse modes in a Fabry-Perot interferometer. We measured the laser emission direction (far-field distribution) and where along the sidewall the light emerged from (image-field distribution) from 100 μm square μ-pillars of GaN and polymer. For GaN square μ-pillars, the emission pattern appears as expected, i.e., cones of radiation emerging from the four corners and parallel to the four faces. For polymer square μ-pillars, the emission pattern is quite different, showing rays emerging at an angle (15°) relative to the sidewall surface and from discrete points along the sidewall surface.

4) People involved in the project

Two capable graduate students (Nathan Rex and Andrew Wing-On Poon) are working on this project. One undergraduate (Jeff Moses) selected the topic of this project as his Senior thesis.

5) Interactions with other institutions

We are continuing and have strengthened our interactions with Professor Joseph Zyss's group at Ecole Normale Superieur at Cachan. They are fabricating polymer micro-structures for us.

We continue our close collaboration with Drs. Steven Hill and Ronald Pinnick from Army Research Laboratory at Adelph, Maryland. Our cooperative agreement grant is focused on bio-aerosol detection by determining the fluorescence spectra of individual ambient aerosols. This is one area that would greatly benefit in having a bright light source in the 290 nm range.

6) Publications

Jean-Pierre Wolf, Yong-le Pan, Gordon M. Turner, Matthew C. Beard, Charles A. Schmuttenmaer, Stephen Holler, Richard K. Chang, "Ballistic Trajectories of Optical Wavepackets within Microcavities", Phys. Rev. A (to be published) (2001).

A. Poon, F. Courvoisier, R.K. Chang, "Multi-mode resonances in square-shaped optical micro-cavities", Opt. Lett.16, 632, 2001.

Andrew W. Poon, Richard K. Chang and Dipak Q. Chowdhury, "Optical fiber cladding diameter uniformity measurement by using whispering-gallery modes: nm resolution in idameter variations along mm – cm length", submitted to Optics Letters, (2001).

Andrew W. Poon, Francois Courvoisier and Richard K. Chang, "Evanescent and refractive side-coupled high-Q resonances of non-circular 2-D micropillars", submitted to Laser Resonators, SPIE/High-Power Lasers and Applications Symposium, San Jose, CA. Jan. 20-26, 2001.

7) Technology transfer/transitions

None

8) Expenditures

On target. Please refer to Yale Grants & Contracts report SF269.

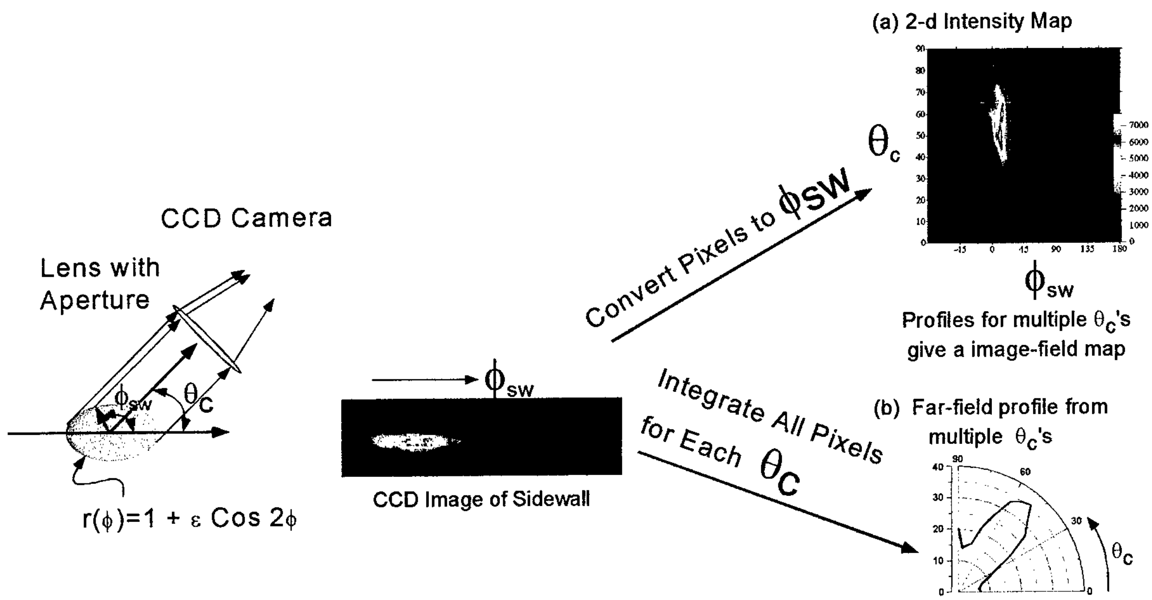

Fig. 1 The experimental setup for imaging of microcavities. Because we study mathematically defined structures, we can convert the sidewall intensity as a function of pixel to intensity as a function of ϕ_{sw}. This gives (a) a 2-d intensity map. The total image intensity as a function of the camera angle gives (b) a farfield intensity distribution.

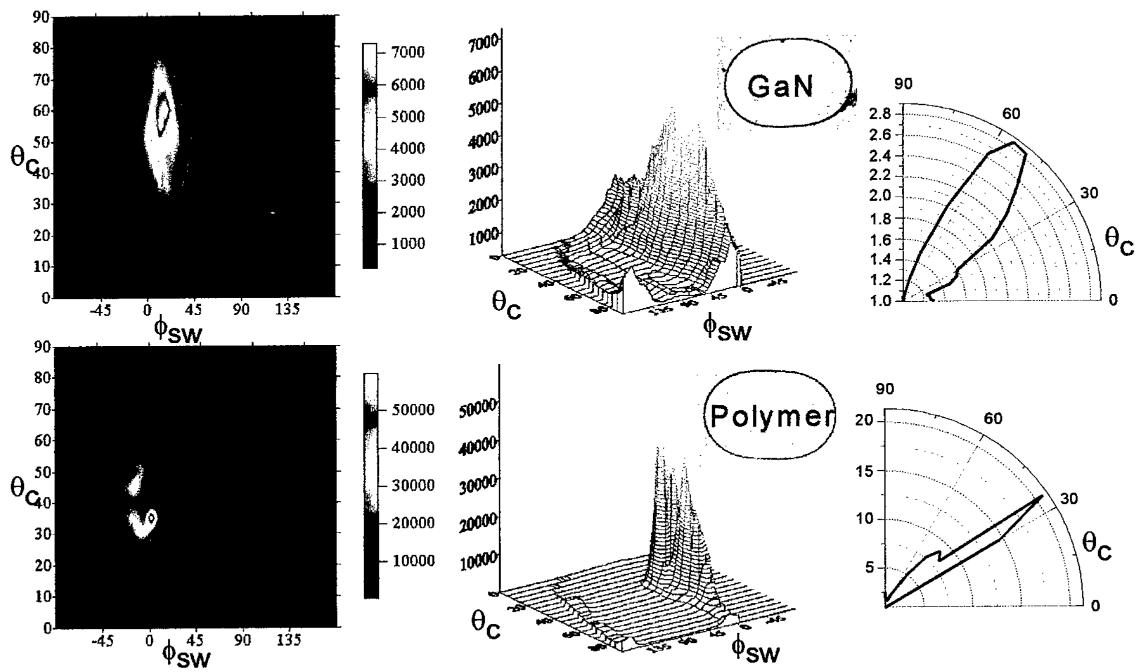

Fig. 2 The comparison of the same microcavity made out of two different index materials. Although the far-field patterns both show directional emission, the 2-d image map shows that the emission is coming from much different locations of the microcavity sidewall.

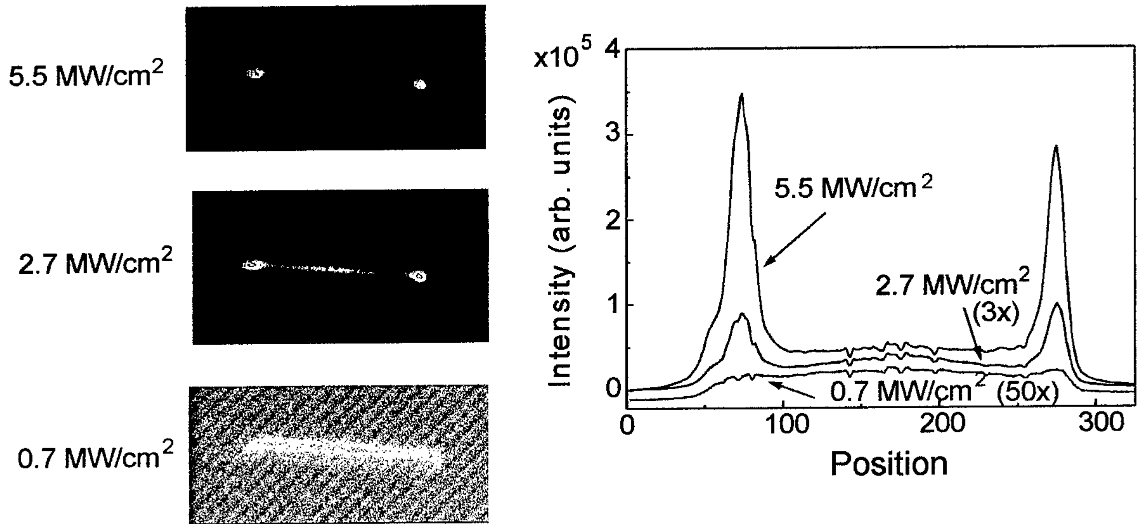

Fig. 3 Pictures of the emission from a GaN square. The emission comes out as lobes from the corners of the square.