Lasing in a One-Dimensional Plasmonic Crystal

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Abstract: We report on the experimental demonstration of laser based on one-dimensional plasmonic crystals. Plasmon radiation has been engineered to create subwavelength mode-volumes smaller than photonic crystals. The device operates with quasi-CW pumping at 77 Kelvin.

I. Introduction

Nanoscale light sources have become increasingly interesting due to their many applications in the study of fundamental cavity-photon interactions [1] and narrow-band light sources for optical interconnects and nanophotonics [2,3]. Plasmonics offers a route to creating subwavelength light sources, allowing electromagnetic mode volumes to be shrunk below the diffraction limit of waves. Plasmonic crystals have been proposed for many different applications including fluorescence enhancement [4] and plasmon confinement [5]. Currently, however, light enhancement in plasmonic crystals has only been demonstrated with dye-based gain media [6]. The integration of *solid-state* gain media with plasmonic crystals shows great promise for the creation of nanolasers where light sources, waveguides, and other photonic/plasmonic devices can be integrated into a single nanophotonic platform. We present a laser based on a one-dimensional plasmonic crystal, which has the potential to attain mode volumes much smaller than photonic crystals, where plasmons are engineered into subwavelength mode volumes with precise control of radiation implied by the design of such crystals.

II. Cavity Design

The cavity was designed by first creating a one-dimensional periodic structure out of InGaAsP on gold with a plasmonic bandgap. It is important to note that the fundamental mode is a surface plasmon mode, not a photonic mode. The fundamental mode has a simulated quality factor Q=100 in a three hole defect (absence of air holes for three periods) in the middle of the beam and an approximate mode volume V_n~0.4 $(\lambda/2n)^3$. This device confines plasmons with dielectric contrast in directions transverse to the crystal length and periodic air-holes in the longitudinal direction of the device. The plasmonic mode can be seen in Fig. 1. By using proper lattice spacing, air hole diameter, and device width, a plasmonic bandgap can be generated which does not allow plasmons of certain frequencies to propagate. For example a laser operating at λ_0~1500nm has a lattice spacing of 330nm, air hole diameters of ~200-230nm, and device widths of ~400nm, allowing devices to be much smaller than traditional photonic crystals (see Fig. 1).

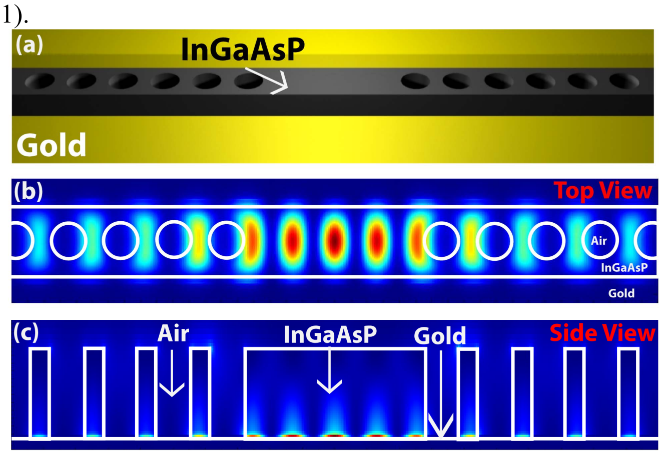

Fig. 1: (a) A schematic of the device, (b) the top view and (c) the side view of the fundamental mode is shown. The color scale represents electric field intensity. The mode volume is significantly reduced due to the surface nature of the plasmonic mode. The crystal structure is outlined in white lines, and the materials are labeled accordingly.

III. Fabrication

The cavity was fabricated with electron-beam metal evaporation, flip-chip bonding, substrate removal, electron-beam patterning of the nanocavity, and subsequent semiconductor etching [2]. In detail, an epiwafer with 200nm of InGaAsP (E_g=0.8 eV) sandwiched between 10nm InP was grown on an InP substrate. A 5nm TiO_2 film was deposited on the sample using ALD (Picosun Sunale R150), followed by 3/80/20nm of Ti/Au/Ti using electron beam evaporation. The substrate was then flip-chip bonded to a sapphire substrate with a polymer bonding layer. The InP substrate was then removed. The device was then patterned into HSQ resist using electron-beam

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lithography. The pattern was then transferred to the active semiconductor material using RIE etching with a combination of hydrogen and methane gases. Finally, the sample was wet-etched to remove sidewall damage. The final fabricated structure can be seen in Fig. 2.

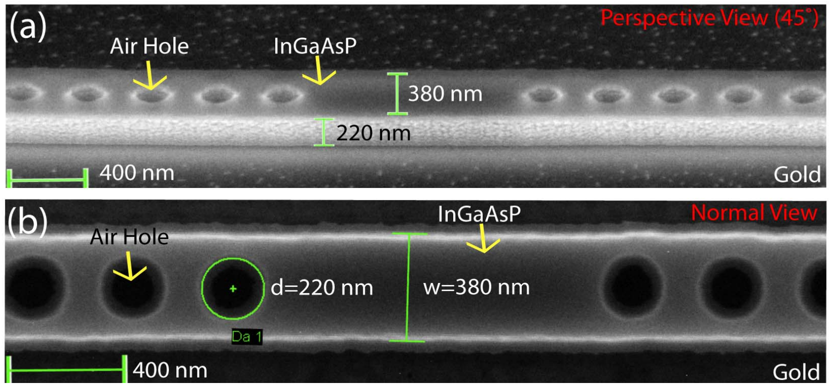

Fig. 2: Scanning electron micrographs of (a) a perspective view and (b) a surface normal view of the final fabricated structure are shown. The final device dimensions are also noted along with scale bars. A semiconductor layer is patterned on a gold film.

IV. Experimental Characterization

The laser characteristics of the device were obtained using a custom-built micro-photoluminescence system with a cooled InGaAs detector integrated with a spectrometer. The resolution limit of the spectrometer is 1nm. The sample was optically pumped at 77K using a 1064nm diode laser with 30ns-10ms pulses with a 0.3-10% duty cycle. Currently, the laser operates at a wavelength of λ_0=1330nm. The laser shows a soft threshold around 800 μW peak pump power. The linewidth of the laser, at maximum pumping power, is limited by the spectrometer resolution. The spontaneous emission of the device outside of the defect mode becomes clamped after threshold is reached. This strongly suggests that all carriers recombine through stimulated emission instead of spontaneous emission. The power dependent lasing spectrum and L-L curve is shown below in Fig. 3.

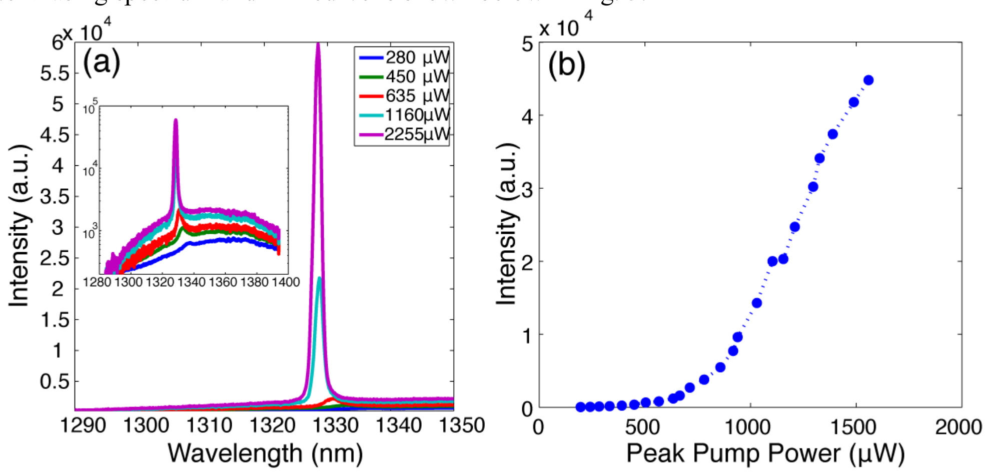

Fig. 3: (a) Power dependent lasing spectrum (inset: log-scale) and (b) L-L curve a characteristic laser is shown. A soft threshold is observed as expected from nanocavity lasers. The clamping of spontaneous emission strongly suggests light evolution by stimulated emission.

V. Conclusion

We have successfully demonstrated lasing from a semiconductor plasmonic crystal cavity. This laser has the potential to be much smaller than photonic crystal cavities and shows potential for use in integrated nanophotonic circuits. This new type of laser will allow nanoscale confinement and radiation engineering in a single structure.

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