SPASERS: Nano-Lasers Going Beyond the Diffraction Limit

Belinda Pacheco Literature Seminar November 9, 2017

A SPASER (Surface Plasmon Amplification by Stimulated Emission of Radiation) is a nanoscale version of a laser that has been recently theorized and experimentally demonstrated.[1,2] SPASERs can be considered counterparts to the laser since they are intense, coherent light sources and require a resonator cavity-like structure with gain media. However, SPASERs dramatically differ from lasers in two ways: 1) their resonator and gain medium structures are on the nanoscale, and 2) the stimulated emission originates from overpopulation of surface plasmons in excited states, and not population inversion in the gain medium. Consequently, SPASERs can uniquely overcome the diffraction limit which is detrimental to the spatial footprint and physical size of the typical laser.[3] Based on these characteristics SPASERs show tremendous prospects in fields where lasers have become limiting factors such as in ultramicroscopy, spectroscopy, ultrasensitive detection, imaging, biomedical applications, optical communications, and lab-on-a-chip devices.[1,4–6] However, SPASERs have not been successfully implemented into these technologies because of their inherent lack of beam directionality and significant radiative losses.[4] Despite their shortcomings, recent efforts in materials chemistry, materials science, and nano-optics have provided routes for overcoming these limitations.

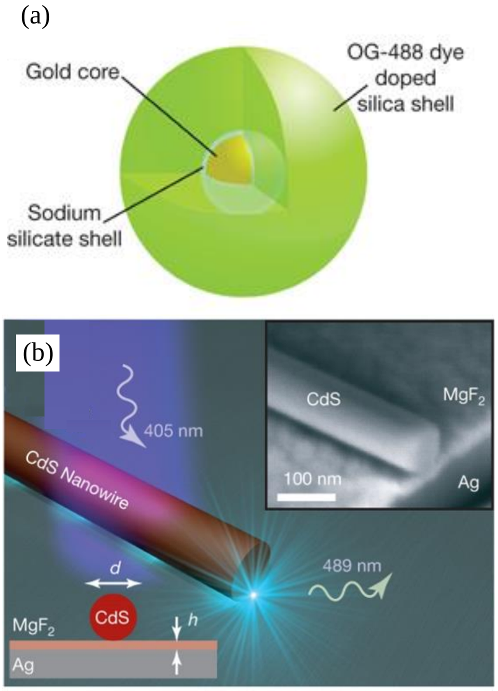

Figure 1. Representations of the first two SPASERS reported in literature. (a) An LSP-based SPASER consisting of a gold-core NP with an outer dye-doped silica shell. Approximated average size according to SEM was 44nm.[9] (b) An SPP-based SPASER achieved from a CdS nanowire on top of a MgF_2 film supported by a silver layer.[10] Inset is a SEM image of a nanowire sliced perpendicular to its axis to show layers.

To understand the lasing action of a SPASER, it is essential to understand the fundamentals of surface plasmons. In essence, surface plasmons (SPs) are oscillations of conduction band electrons at the interface between materials of different dielectric permittivity.[7] SPs are naturally coupled to electromagnetic waves allowing them to be considered a type of boson (a polariton), thereby acting similarly to photons (i.e. capable of stimulated emission).[1,2] In practice, SPs take on one of two forms- Surface Plasmon Polaritons (SPPs) or Localized Surface Plasmons (LSPs). The former can be described as quantized, transverse magnetic waves that propagate at a metal-dielectric interface that is excited by light. LSPs occur when a particle much smaller than the excitation wavelength is being excited by light causing it to experience plasmon oscillations locally.[3,8]

The first SPASER was experimentally demonstrated in 2009 and functioned off of the LSP mechanism.[9] This seminal work synthesized nanoparticles (NPs) with a gold core and a dye-doped silica shell to act as the resonator cavity and gain, respectively (Figure 1a). As can be expected for a first demonstration, this system was not optimal and revealed unfavorable characteristics of a SPASER. For one, the quality factor (Q) which relates the quality of the plasmonic/photonic modes and cavity losses was detrimentally low. The Q-factor was found to be 14.8, whereas optical resonators in lasers often have Q-factor values between 10^3-10^4 or higher. Furthermore, there was no mention of beam directionality in this study which is an essential characteristic of a laser. The second demonstration of a SPASER came only one month after and introduced a new SPP-based prototype for the SPASER.[10] As seen in Figure 1b, cadmium sulfide semiconducting nanowires were spin-coated onto an MgF_2 film supported by a silver surface for this prototype. Although this technique improved dissipative energy losses, all experiments had to be conducted at temperatures <10 K for optimal lasing. Further, the problem of beam directionality still had no solution.

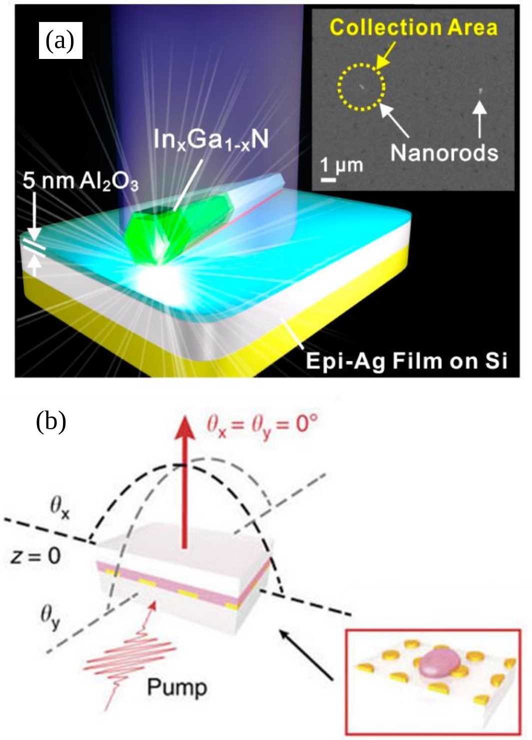

Figure 2. (a) Diagram of the structure for the InGaN/GaN nanorod tunable SPASER. The inset demonstrates shows an SEM images of the collection area for emission that was produced upon optical pumping.[11] (b) Representation of the structure and configuration of Au Np arrays used for the directional and dynamically tunable SPASER discussed.[14]

Recently, there have been increased efforts to address the drawbacks of SPASERs, many of which have heavily relied on advances in materials fabrication methods and techniques. One such study includes work greatly reminiscent of the SPP-based SPASER previously mentioned. This SPASER demonstrated static tunability across most the visible spectrum by employing a metal-oxide-semiconductor nanostructure platform (Figure 2a).[11] Tunability was achieved by varying the indium content in InGaN/GaN core-shell nanorods grown by plasma-assisted molecular beam epitaxy. Lasing action was accomplished by drop casting the nanorods on a highly uniform Al_2O_3 layer supported on an epitaxial Ag film. Using this construct, the Ag film/Al_2O_3 layer can be equated to the photonic resonator and the InGaN/GaN nanorods to the tunable gain medium. Despite providing significant advances to the field, this SPASER was only able to reach optimal lasing conditions at temperatures of 7K and the static stability of this system would make it difficult to implement commercially.

Several experimental and theoretical studies have aimed to address the lack of directionality in SPASERs.[12,13] One such study not only proposed a synthetic strategy to produce directional lasing, but also a platform for lasing that could be conducted at room temperature with dynamic tunability.[14] Operating off of the LSP regime, a periodic array of gold NPs was fabricated using the PEEL technique which is a combination of **P**hotolithography, **E**tching, **E**lectron-beam deposition and **L**ift-off (Figure 2b). Additionally, a microfluidic channel filled with index-matched liquid gain and the Au NP array realized dynamic lasing tunability across the bandwidth of the dyes used. While the study did make strides in addressing several of the limitations on SPASERS, there was a notable decrease in lasing stability in the dynamically tunable system. Similarly, line broadening and lasing intensity suffered with increased dye concentration and pump power, respectively.

SPASERs have promising prospects in the fields of nanoscale physics, microscopy, spectroscopy, imaging, biomedical applications, and optical communications due to their unique ability to beat the diffraction limit and their physical size. However, there are still many drawbacks left to address to fully implement them in to technology and commercial goods. The most logical progression for future work would be to optimize current systems for improved directionality and fewer radiative losses. Beyond that, there are several limitations that have yet to be addressed by literature. For example, how to take SPASER pulses into the femtosecond regime; and what forms and structures of materials will be needed to create "optics" compatible with SPASERs? Also, how can SPASERs be integrated to photonic circuits for on-chip applications? If these and other questions can be addressed, it will be possible to set the stage for SPASERs to do in the field of nano-optics what lasers have done for conventional optics.[1]

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