Surface plasmon lasers

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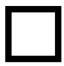
Summary

Surface plasmons (SPs) are surface waves at the interface between a dielectric and a good metal, such as silver and gold, and are formed by the interaction between light and the free electrons at the metal-dielectric interface. They provide strong field confinement for optical fields, opening new possibilities for enhanced light-matter interaction. Surface plasmons can be efficiently coupled to free-space photons by scattering on a periodic lattice of nanometer-size holes, i.e., a metal hole array.

Lasers are known to emit coherent, monochromatic, and strongly directional beams. There are two essential components to a laser: a (pumped) gain medium and a resonator. The gain medium amplifies the field and the resonator confines the laser mode and supplies the feedback needed to obtain coherence.

In this thesis, we describe experiments on SP propagation and SP lasing in active two-dimensional metal hole arrays operating at telecom wavelengths ($\lambda \sim 1500$ nm) and cryogenic temperatures. The gain is provided by an optically pumped InGaAs semiconductor layer closely spaced to a metallic gold film. A resonator for SPs is created by scattering on an array of holes in the gold film. As the feedback in metal hole arrays is distributed over the whole device, we are dealing with a distributed feedback laser instead of a Fabry-Pérot laser. Distributed feedback lasers provide a strong laser mode selection and stable operating wavelength.

We have studied such active hole arrays with square and hexagonal lattice symmetries both below and above their lasing threshold. We have investigated the role of the symmetry of the lattice on the SP propagation and SP lasing. We have explored the laser frequencies and the feedback mechanism of these SP lasers, and observed the spatial profile and direction of the emitted laser beams. The structure of this thesis is depicted schematically in the table below. The following paragraphs will give an overview of the contents of each chapter.

		
Below threshold	**Chapter 2** SP dispersion & SP scattering **Chapter 3** Loss & SP-photon scattering	**Chapter 5** SP-SP scattering & link to single hole scattering
Above threshold	**Chapter 4** Intensity, phase & feedback	**Chapter 6** Tuning between lasing in two modes

In order to understand SP lasing in metal hole arrays, we first need to understand SP propagation in metal hole arrays which can be studied by operating the SP lasers below their laser threshold. In chapter 2 we study metal hole arrays with a square lattice. We obtain the resonance frequencies from angle-dependent spectra and identify four SP bands. These four bands emit light with distinct polarizations. Three bands emit p-polarized light and one band emits s-polarized light. We develop a theoretical framework that quantitatively predicts these bands. This coupled-mode model is a central component in the thesis. Its main constituents are traveling SP waves in four directions and scattering of these traveling waves by the holes. This scattering couples the traveling waves, and thereby produces standing-wave components and induces energy splittings between the bands. We link the observed splitting between bands to scattering of SPs on the holes.

Which laser mode is active depends on the gain and loss of the available modes. In chapter 3, we identify and quantify the loss mechanisms of SPs in metal hole arrays by measuring the linewidths and intensity of the SP modes below laser threshold. The main loss channels are radiative loss and ohmic loss.

SP lasers in metal hole arrays emit donut shaped beams, i.e. the emission is limited to a small ring with a dark center. In chapter 4 we unravel mechanisms that are responsible for this feature. In order to understand what is happening inside the device, we measure the field profile of the laser beam, i.e., we observe both the intensity and the phase of the emitted light. The phase was retrieved with a novel beam-block method and an iterative algorithm. SP lasers in square arrays emit donut shaped beams that have a radial polarization profile. The observed fields do not agree with standard one-dimensional distributed feedback theory. We identify position dependent gain as the missing element, extend the distributed feedback theory with it, and find good agreement between theory and experiment. This is a prime example in which the observation of the phase of a wave phenomenon gives vital information about the studied problem.

In contrast to lattices with a square symmetry, lattices with a hexagonal symmetry have principal directions that are not perpendicular. In chapter 5 we study the influence of the lattice symmetry on the SP propagation by measuring the optical dispersion of three hexagonal based lattices with increasing complexity in the unit cell: hexagonal, honeycomb and Kagome. We retrieve angle-dependent scattering rates of these lattices and find that these rates are dominated by the hole density and not by the complexity of the unit cell. The observed angle-dependent scattering can be explained by a single-hole model based on electric and magnetic dipoles.

In chapter 6, we demonstrate SP lasing in hexagonal plasmonic crystals. We observe lasing in two modes with different polarization and intensity profiles. Tuning between these modes is achieved by changing the size of the pump spot. We link this observation to previous experimental and theoretical work on photonic crystals. Furthermore, we explain the mode and polarization profiles from symmetry arguments and show that a compact description of the mode profiles can be given in terms of a sum of orbital angular momentum (OAM) beams.