Two-dimensional optics : diffraction and dispersion of surface plasmons

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1 Introduction

A SURFACE PLASMON is a light wave bound to a metal surface, first predicted in 1957 as a side-effect of bombarding metal films with fast electrons[1] and observed two years later.[2] Surface plasmons occur in many different geometries of metal, from nanoparticles[3] to flat metal surfaces. This dissertation is about the latter type, which propagates along the two-dimensional metal surface, as opposed to 'normal' light which travels through three-dimensional space, as a sort of two-dimensional light wave.[4] The surface plasmon's restriction to the metal surface allows us to send optical signals through channels of extremely small size.[5]

This chapter is a short scientific introduction to the work described in this thesis. Readers interested in an introduction accessible to non-scientists should turn to page 1.

[1] Ritchie, 1957.

[2] Powell and Swan, 1959.

[3] Moskovits, 1985.

[4] Bell et al., 1975; Bozhevolnyi and Pudonin, 1997; Ditlbacher, Krenn, Schider, Leitner, and Aussenegg, 2002.

[5] Maier and Atwater, 2005; García-Vidal, 2006.

1.1 Devices using subwavelength slits in metal films

IT HAS BEEN KNOWN FOR SOME TIME[6] that a very narrow slit or scratch in a thin metal film, under certain circumstances, can convert incident light with the correct polarization into surface plasmons, and vice versa. Which metal is used makes an important difference.

[6] Jasperson and Schnatterly, 1969; Sánchez-Gil and Maradudin, 1999; Lalanne, Hugonin, and Rodier, 2005; Schouten, Kuzmin, et al., 2005.

Such conversions take a three-dimensional optical mode and change it to a corresponding two-dimensional one, and back again.[7] This conversion is sensitive to the mode's local phase front. This influence of phase, and the aforementioned sensitivity to polarization, allow all sorts of surface plasmon effects having to do with polarization, phase, or both.

[7] Altewischer, van Exter, and Woerdman, 2002.

In chapter 2, taking a metal film made of gold, 200 nm thick, we examine how much light is transmitted through slits of varying thicknesses from 50 to 500 nm, and how this transmitted light is polarized. Surface plasmons are excited at one particular polarization, and we exploit this to control the polarization of the transmitted light. At a certain slit width and film thickness, the slit turns out to be able to convert linearly polarized light into circularly polarized, and vice versa. We also developed a simple model that explains this phenomenon in an intuitive way, by viewing the slit as a waveguide with imperfectly conducting walls, albeit a very short one. Our approach provides a convenient way to implement the functionality of a quarter-wave plate at a very small scale.

We exploit this phenomenon again in chapter 3; this time with circular slits, where the slit creates an optical vortex from circularly polarized light, thereby converting optical spin angular momentum[8] to optical orbital angular momentum.[9] This curious interaction due to symmetry has been studied in birefringent materials,[10] space-variant gratings,[11] and even in electron beams.[12]

[8] Beth, 1936.

[9] Allen, Beijersbergen, Spreeuw, and Woerdman, 1992.

[10] Ciattoni, Cincotti, and Palma, 2003; Marrucci, Manzo, and Paparo, 2006.

[11] Bomzon, Kleiner, and Hasman, 2001; Lombard, Drezet, Genet, and Ebbesen, 2010.

[12] Karimi, Marrucci, Grillo, and Santamato, 2012.

Chapter 4 describes an experiment with two very narrow slits milled parallel to each other in a very thin gold film. One slit is illuminated with light, and at the slit it is partly converted to surface plasmons. The surface plasmons travel across the film to the other slit, where they are converted once again into light, and we record the light intensity distribution; during transit, the shape of the plasmon wavefront changes due to diffraction. We use this diffraction to retrieve information about the incident light's phase; the phase cannot be measured directly, a well-known problem in physics,[13] and is usually probed using interference with a second light beam.[14] In order to demonstrate this technique, we measure the phase of beams containing various optical vortices. This technique could produce a wavefront sensor with a much higher spatial resolution than achievable with the usual techniques, which could be interesting for astronomy and UV lithography.

[13] Fienup, 1982.

[14] Baranova, Zel'dovich, Mamaev, Pilipetskii, and Shkunov, 1981.

1.2 *Anomalous dispersion of surface plasmons*

DISPERSION IS THE PHENOMENON of the velocity of light in a material depending on the light's wavelength. For example, if we send a pulse of red light and a pulse of blue light into a glass brick at the same instant, they will emerge from the other side at different times. Usually the red light arrives earlier than the blue light (which is called "normal dispersion"), but sometimes the reverse is true: "anomalous" dispersion. Anomalous dispersion is a prerequisite for solitons, light pulses that can travel a long distance without changing their shape. Anomalous dispersion is needed to balance the normal dispersion caused by the other prerequisite for solitons, the Kerr effect. When the two occur together, they can cancel each other out, allowing a pulse that propagates without changing. There have been several, mainly mathematical, proposals for surface plasmon soliton pulses in recent years.[15]

[15] Feigenbaum and Orenstein, 2007; Bliokh, Bliokh, and Ferrando, 2009; Davoyan, Shadrivov, and Kivshar, 2009; Sámson, Horak, MacDonald, and Zheludev, 2011; Marini, Skryabin, and Malomed, 2011; Walasik, Nazabal, Chauvet, Kartashov, and Renversez, 2012.

Anomalous dispersion mostly occurs in the neighborhood of wavelengths that the material absorbs. An ideal metal behaves according to the free-electron model, or Drude model, where there are no absorptions, and the dispersion is always normal, in the frequency region of metallic behavior. However, the metal aluminum has an absorption in the near infrared,[16] a so-called parallel-band absorption,[17] which we aim to exploit. In the second part of this work, we try to answer the question of whether this absorption also causes surface plasmons on an aluminum surface to have anomalous dispersion. We probe this using a method where the surface plasmons are excited by incoming light from a prism. This technique has two variations, named after the German physicists Kretschmann[18] and Otto.[19] The Otto configuration is generally considered to be disadvantageous compared to the Kretschmann configuration. In chapter 5, we show that that is a misconception. In addition, we introduce a method of analysis with which we can properly interpret experimental results using lossy metals in both configurations, which is impossible with the usual approach.

[16] Strong, 1936; Bennett, Silver, and Ashley, 1963.

[17] Harrison, 1966.

[18] Kretschmann, 1971.

[19] Otto, 1968.

Chapters 6 and 7 describe the results of measuring surface plasmons with anomalous dispersion. In chapter 6 we demonstrate the existence of surface plasmons with anomalous dispersion on an aluminum surface. Subsequently, in chapter 7, we increase the degree of anomalous dispersion (expressed in the second-order dispersion parameter) by a great deal, by cooling the metal to near the temperature of liquid nitrogen, approximately 86 K. However, there is a tradeoff between more anomalous dispersion and more surface plasmon loss, because the surface plasmons decay more quickly in the low-temperature metal: the parallel-band absorption also becomes stronger at low temperatures.[20]

[20] Liljenvall, Mathewson, and Myers, 1971; Mathewson and Myers, 1972.