Two-dimensional optics : diffraction and dispersion of surface plasmons

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Preface (Introduction for non-scientists)

A *SURFACE PLASMON* IS A LIGHT WAVE that is trapped on a flat two-dimensional surface, henceforth called Flatland, as in a famous novel.[1] Many devices and effects that are familiar from normal, three-dimensional optics also exist in Flatland, usually created by applying some sort of material or structure to the surface. For example, there are mirrors (Figure 1) and lenses (Figure 2).

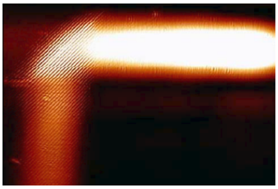


Figure 1: A Flatland mirror, seen from above; it is tilted at 45°. The surface plasmon enters from the right side of the figure and is partially reflected downwards. (Reprinted from González et al. (2006), with kind permission of the author. Copyright 2006, the American Physical Society.)

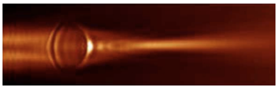


Figure 2: A Flatland lens, seen from above. The surface plasmon enters from the left side of the figure and is focused to a small spot about halfway through the figure. (Reprinted from Devaux et al. (2010), with kind permission of the Optical Society of America.)

Surface plasmons are special because they can only exist on the boundary surface between a metal that conducts electricity very well, like silver or gold, and a non-metal substance, such as glass, plastic, or air. (As always in science, there are exceptions to this rule: semiconductors can also work instead of metals,[2] and just recently a layer of graphene was proposed.[3]) The metal has to be a good conductor, so that some of the electrons belonging to its atoms, called *free electrons*, can move more or less unhindered through the metal, from atom to atom. Surface plasmons cannot exist without free electrons.

In an ocean wave, the water level rises and dips, but nothing like that happens in Flatland. In a surface plasmon, the wave is connected to back-and-forth movements of the free electrons in the metal. Moving electrons create a wave on the outside of the metal, and the wave moves other electrons inside the metal, which is how surface plasmons move.

Surface plasmons being trapped on the metal's surface, or *confined*, is actually one of the desirable properties of surface plasmons, and partly explains why they are such a popular research subject. Transforming light into surface plasmons allows light to squeeze into tiny spaces, smaller than it would otherwise be able to fit into. The more you try to confine regular light, the more it tends to spread out, and if you try to cram light into a channel that is too small to contain it (less than half the light's wavelength), then it simply won't fit.[4] Surface plasmons, however, can be stuffed into tiny strip-shaped metal channels[5] or grooves.[6] Researchers can use them to develop ultra-small components for circuits that carry

[1] Abbott, 1884.

[2] Gómez Rivas, Kuttge, Kurz, Haring Bolivar, and Sánchez-Gil, 2006.

[3] Gorbach, 2013.

[4] Although that is a simplification; more about that in chapter 2.

[5] Maier and Atwater, 2005.

[6] García-Vidal, 2006.

light instead of electricity: this is the field of *nanophotonics*.[7] Even though surface plasmons were discovered over fifty years ago, nanotechnology has only caught up in the last ten to fifteen years and made nanophotonics possible.

Another important property of surface plasmons is that confining the light into a small space squeezes all the energy it carries into a small space too — this effect is known as *field enhancement*. Researchers can then do processes that require a lot of energy without needing a lot of light, because all the light's energy is concentrated in one tiny place. This is also important for antennas in nanophotonics.[8] An antenna is nothing more than a device that converts free radiation (cell tower signals) into localized energy (the electronics in your mobile phone) and vice versa. We can engineer tiny metal antennas in such a way that they have a single spot where the field enhancement is very large. If we position a molecule at that spot, the molecule can broadcast its energy very efficiently through the antenna. So a good plasmonic antenna is an efficient bridge between molecule-sized phenomena and human-scale signals in the laboratory.

One problem with engineering photonic devices is that light is damped when it interacts with metals. The light's energy is simply converted into heat. Obviously, that is a nuisance, but as is usual in science, someone has figured out a way to turn it into an advantage. Researchers are working on an experimental cancer treatment that works with tiny particles called "nanoshells" coated with a thin layer of metal.[9] These nanoshells can be attached to antibodies that seek out cancerous tissue and congregate in the tumor cells. Infrared light normally passes harmlessly through body tissue; however, the nanoshells are engineered to act as receiver antennas for the light, absorbing it and concentrating all the energy in a small space. The resulting release of heat kills the cancer cells.

For further reading, I recommend a 2007 *Scientific American* article about surface plasmons and their applications.[10] For a more technical review of the latest developments, there is an open-access article in *Journal of Physics D*,[11] only a few months old at the time of writing.

Polarization and holes in metal sheets

THE CURRENT WAVE of surface plasmon research was unleashed when Thomas Ebbesen at NEC Corporation asked a technician to make a grid of tiny holes in a metal sheet. When Ebbesen picked up the sheet he was surprised that he could partially see through it even though the holes were supposedly tiny enough that hardly any light should have been able to

[7] Nano is a word meaning, roughly, smaller than one micron. It refers to the realm of objects the size of a cell membrane, a virus, or one one-thousandth of a human hair.

[8] Novotny and van Hulst, 2011.

[9] Loo, Lowery, Halas, West, and Drezek, 2005.

[10] Atwater, 2007.

[11] Hayashi and Okamoto, 2012.

get through. Moreover, the transmitted light was colored, and the color changed when he turned the sheet and viewed it at an angle. He first thought the technician had made a mistake and drilled the holes too large, but when it became clear that there was nothing wrong with the holes, he and his co-workers hit upon surface plasmons as an explanation. This resulted in a landmark paper[12] and the discovery of an effect called *extraordinary optical transmission*.

Simply speaking, light falling on a small enough hole in a thin metal sheet launches surface plasmons into Flatland from the edge of the hole. These surface plasmons travel across the metal sheet to the next hole, where they turn into light again and pass through the hole. This extra light augments the small amount of light that was already traveling through the hole; combined, enough light travels through the metal sheet for it to be translucent.

Chapter 2 describes research where the opposite result occurs; we studied rectangular-shaped slits in a metal sheet, but only one slit at a time. Studying the slits in isolation means that they still launch surface plasmons from their edges, but since the surface plasmons have no other slits to go to, they just travel through Flatland to nowhere and eventually die out. This actually causes *less* light to make it through the slit than otherwise would.

We use this effect to create a tiny version of a device called a *quarter-wave plate*. It takes light with *linear polarization* and converts it into *circular polarization*. Polarization is best thought of as two people, Alice and Bob, holding opposite ends of a long rope (Figure 3). If Alice wishes to send a wave to Bob over the rope, she shakes her end back and forth, and a wave travels down the rope to Bob. The rope oscillates back and forth in one plane, and we call this *linear polarization*. However, Alice can also spin her end of the rope in a circle, in which case a circular wave travels down the rope to Bob; we call this *circular polarization*. There are even two variations, depending on whether Alice spins clockwise or counter-clockwise, called *left-handed* and *right-handed*. Light can do the exact same thing.

Since a quarter-wave plate converts linear polarization to circular, it is as if Alice sends a linearly polarized wave to Bob, but by the time it reaches Bob it has become circularly polarized. This polarization change doesn't happen in a rope, but it does happen in light. Quarter-wave plates are present in 3D projection systems: the image meant for your left eye is projected with left-handed circular polarization, and the one for your right eye is right-handed. Filters in your 3D glasses make sure that each

[12] Ebbesen, Lezec, Ghaemi, Thio, and Wolff, 1998.

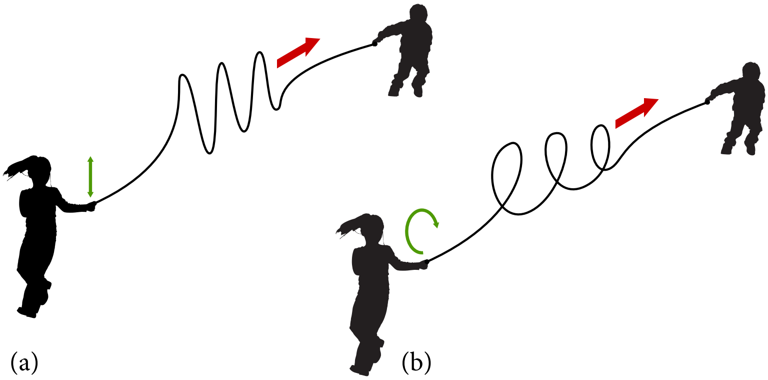


Figure 3: (a) Alice is sending a linearly polarized wave to Bob. (b) Alice is sending a left-handed circularly polarized wave to Bob.

eye only sees the correct image.

Just as in Ebbesen's extraordinary optical transmission, this miniaturized quarter-wave plate also stems from an accidental discovery: in 2005 my co-worker Nikolay Kuzmin discovered by chance that circularly polarized light was coming out of the back sides of slits in a metal sheet.[13]

We continued this line of research in chapter 3, using the effects explored in chapter 2 to build a device that converts light with *spin angular momentum* into light with *orbital angular momentum*. Consider the Earth: our planet has spin angular momentum because it revolves around its own axis, causing day and night. The Earth also has orbital angular momentum because it orbits around the Sun, which causes the seasons. Particles of light also have both of these kinds of angular momentum. In fact, a light particle spinning around like a top is just another way of looking at circular polarization. Light is both a particle and a wave; spin angular momentum is to a light particle as circular polarization is to a light wave.

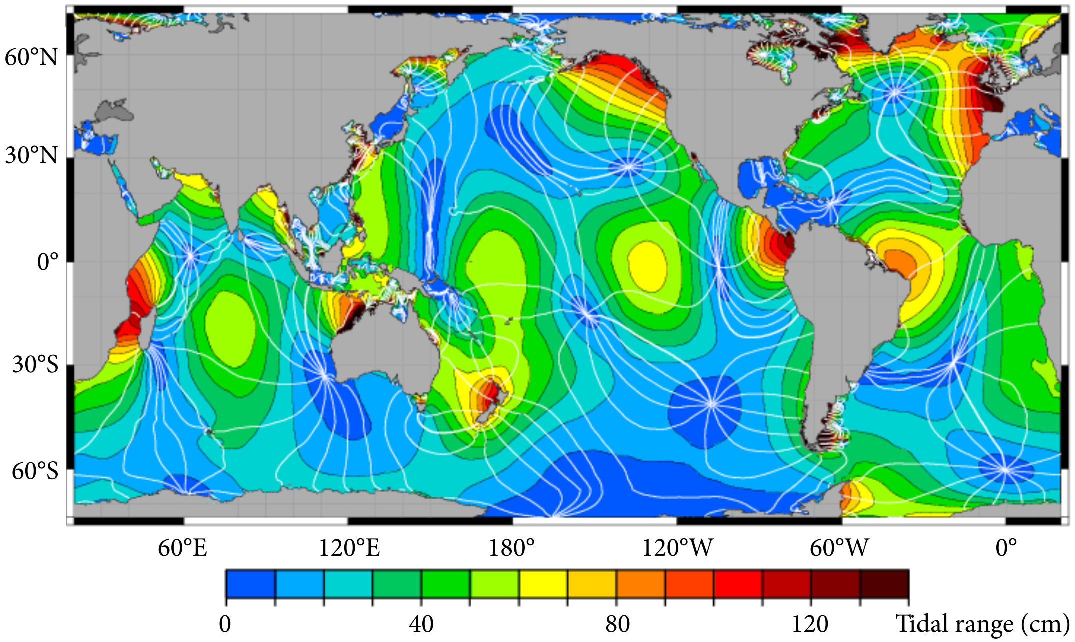
Phase vortices

SIMILARLY, ORBITAL ANGULAR MOMENTUM is to a light particle as *phase vortex* is to a light wave. "Phase vortex" sounds as if it came straight out of *Star Trek*, but it can be easily illustrated with a nice piece of oceanographical research from NASA[14] (Figure 4.)

The ocean tides exhibit phase vortices. For example, we can see one in the middle of the Pacific Ocean, at about 15° south and 150° west. It is not a whirlpool; in fact, if you were to travel there, you would notice nothing special about that spot. The white lines indicate places where it is high tide at the same time; each line is an hour earlier or later than its neighbor. We could say that the instant of high tide "rotates" around the

[13] Kuzmin, 2008, pp. 73–87.

[14] Ray, 2006.



phase vortex. So when the lines all meet in the center of the phase vortex, then when is it high tide? Always? Never? The answer is that the phase vortices are always in the blue regions where the tide is weakest: there is no tide there!

Light can do the same thing: we can create a laser beam where the "high tide" of the light wave rotates around the center of the laser beam. Since there is no tide in the center, the laser beam is dark there. We can also have two, three, or more high tides rotating around one laser beam, and they can go clockwise or counterclockwise: the number of high tides is called *topological charge*. These laser beams with dark holes in the middle, also called *donut beams*, can be used to encode information densely.[15]

So, converting spin angular momentum to orbital angular momentum, as we describe in chapter 3, means that we create a donut beam out of a circularly polarized laser beam with no donut. Returning to the example of the Earth, it is as if we could make it spin slower but orbit faster, thereby lengthening the day and shortening the year. Hitting the Earth with a giant comet would do that, but that requires the comet to contribute its angular momentum. With our device, we can create donut beams non-destructively, without adding or losing angular momentum.

One problem with donut beams is that they are hard to identify. The donut part is easy to see, but light waves are so fast (trillions of cycles per

Figure 4: Tides in the world's oceans. Along each white line, it is high tide at exactly the same time, and neighboring white lines' high tides are separated by one hour. The colored spaces represent the tide strength (blue is weaker and red is stronger), and the amplitude is indicated in centimeters. (Public domain image. Credit to NASA Goddard Space Flight Center; NASA Jet Propulsion Laboratory; Scientific Visualization Studio; Television Production NASA-TV/GSFC. Special thanks to Dr. Richard Ray, Space Geodesy branch, NASA/GSFC)

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[15] Padgett, Courtial, and Allen, 2004; Molina-Terriza, Torres, and Torner, 2007.

second) that it's completely impossible to measure the number of high tides directly, or the direction in which they are rotating. However, we need to know this information in order to use the beams. The usual way of determination involves using a second laser beam to probe the first one. However, with the research in chapter 4 we have created a device where the second laser beam is not necessary. We used another metal sheet with two slits: one to launch surface plasmons into Flatland and one to catch them and take them out of Flatland. The slit takes a "slice" of the phase vortex, similar to the way that a longitude line in Fig. 4 represents a slice of the ocean. By examining the surface plasmons caught at the second slit, we can recover all the information we need about the phase vortex: topological charge, and whether it is rotating clockwise or counterclockwise.

Aluminum and solitons

THE SECOND PART of this dissertation examines surface plasmons traveling on an aluminum surface. Most surface plasmon research uses gold or silver because these materials absorb less light. Aluminum absorbs light in a certain frequency range, which makes it less desirable for some uses. However, we are interested in aluminum specifically because of this feature!

The familiar shiny gray color of a polished metal surface arises when the metal reflects all the colors of visible light approximately equally. Figure 5 shows what percentage of light of each color aluminum reflects (as well as light that is invisible to the human eye and therefore has no color: ultraviolet to the left and infrared to the right.) We see that this is true for aluminum as well, but something else happens in the infrared, to the right of the visible part of the spectrum: aluminum reflects less light and absorbs more.

In order to see why this is interesting we need to think about a *soliton*: a short wave that remains unchanged as it travels along. Ocean waves, for example, break and disperse, while short light pulses get longer and spread out more as they travel. Solitons, on the other hand, do not. John Scott Russell discovered them by chance in 1834 when he observed one in Scotland's Union Canal. Figure 6 shows a modern-day reconstruction of the discovery. Solitons remained an oddball curiosity for over a century until they found an application in fiber-optic communications: the ability to send a pulse of light through a fiber without any distortion proved invaluable.

Since pulses disperse in any material, the existence of a soliton depends

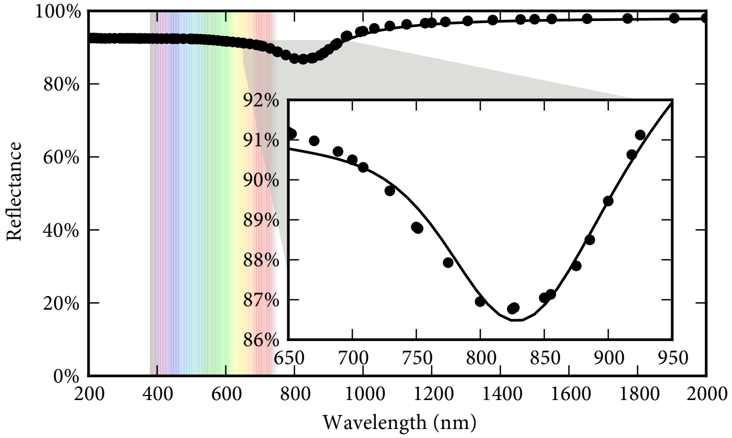

Figure 5: Percentage of light reflected by aluminum, versus wavelength of the light (color). To the left is ultraviolet light (invisible to human eyes), then visible light (indicated by a rainbow of colors), and to the right of that is infrared light (again invisible.) About 93% of visible light is reflected, but there is a downward dip in the near infrared, which is what we are interested in here. The dots and the solid line indicate measurements from two different sources (Smith, Shiles, and Inokuti, 1985; Rakić, Djurišić, Elazar, and Majewski, 1998.) The inset shows the interesting region in detail.

on two opposite effects that counterbalance each other. One of these effects, where blue light travels faster through the material than red light, is called *anomalous dispersion*.[16] It is often found paired with an absorption such as that of aluminum, shown in Fig. 5. Anomalous dispersion can be counterbalanced by something called the *Kerr effect* in order to create a soliton, whereas normal dispersion can't. This is why anomalous dispersion is an interesting subject of research.

Aluminum itself is not a good material for transporting solitons, for the simple reason that it is opaque and therefore not very good at transporting light pulses. However, aluminum paired with another material could create some of the conditions for a surface plasmon soliton! It is with this in mind that we conducted the research described in chapters 5, 6, and 7.

Chapter 5 is a discussion of how to conduct and interpret surface plasmon measurements. We discovered in the course of our aluminum research that one of the usual methods for probing surface plasmons, called the *Kretschmann configuration*, does not work as well for surface plasmons on aluminum as it does for gold and silver. The aluminum measurements are more difficult to interpret, so one of the new findings of chapter 5 is an effective method of interpreting them. We also find that a different arrangement of the experiment, called the *Otto configuration*, is actually quite useful under these circumstances, even though it is usually considered less effective than the Kretschmann configuration.

In chapter 6, we demonstrate the first measurements of anomalous dispersion for surface plasmons, and in chapter 7, we show how cooling down the aluminum with liquid nitrogen enhances the effect quite a bit.

[16] This is a terribly inappropriate name, because anomalous dispersion is not an anomaly at all: it is present in most materials. 'Anomalous' implies that it's rare or not understood, but in this case it's simply the opposite of normal dispersion, where red light travels faster than blue light in a material.

Figure 6: Modern-day reenactment of Scott Russell's discovery of solitons in the Union Canal. (Figure reprinted from "Soliton wave receives crowd of admirers" (1995), with license.) The soliton is visible as the "mountain" of water behind the boat.

With this discovery, we are one step closer to creating a surface plasmon soliton and the Flatland analog to fiber-optic technology.

THE COMMON THEME through all of this research is finding and exploring the Flatland equivalents of phenomena from optics in the normal, three-dimensional world, such as solitons. We also exploit Flatland effects to bring about other phenomena in three-dimensional optics, such as spin-to-orbit conversion. In the future, as surface plasmons become more and more important, from antennas to sensors to curing cancer, technology will move more into Flatland. For this, we need to have a Flatland 'engineering toolbox' that is as complete as our three-dimensional engineering toolbox that has been filled gradually over the past few centuries.