Chapter 2
Cloaking Devices: Vanishing Into Thin Space

I've served on a half a dozen ships, and none of them've had cloaking devices except the Defiant. Now that we're not using it, I feel naked.

—Miles O'Brien
DS9: Broken Link

2.1 Introduction

Invisibility has been a mainstay of fantasy and science fiction stories for decades. H.G. Wells' *The Invisible Man* had chemistry and biology at the heart of the story of a man rendered permanently invisible by the chemical, monocane. Griffin, the scientist in Wells' story of science and morality, developed a method to change the way human flesh was affected by light; it neither reflected nor absorbed any part of the visible spectrum. Wells was prescient in many of his stories; but even he couldn't imagine just how close he was to early 21st century science's ability to make things invisible.

What could be cooler than moving around without anyone else knowing you are there. You could get away with anything; a license to act badly. Teachers often try to get students to think about the moral dilemma attached to invisibility, they ask students what they would and wouldn't be willing to do if they were invisible. For example, Wells' antagonist Griffin was driven mad by his invisibility and was finally beaten to death by a mob after carrying out a murder spree. His lesson was that invisibility may not be all it's cracked up to be—and Gene Roddenberry was well aware of the moral tightrope one might walk if unseen.

Roddenberry believed in the idea of heroes and fair play. That's why the starships and fighters of the Federation of Planets didn't have cloaking devices. Roddenberry stated in several interviews that, "heroes don't sneak around." To his way of thinking, jumping out of the dark to hit an opponent when they weren't expecting it was not something that those who commanded the moral high ground would do. However, Gene and the myriad writers of the *Star Trek* episodes and movies were more than willing to give some species this technology, it was just too

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cool a toy to leave out of the franchise. The Klingons, the Romulans, the Borg, the Suliban, the Cardassians—it would be easy to think that only evil empires developed cloaking if the Klingons hadn't later decided to join the good guys. Even the Federation dabbled in cloaking from time to time, either as a means to level a playing field (*DS9*: *The Search, parts I and II*), or sometimes as a tool used by rogue Federation officials as they slipped down that slippery moral slope (*TNG*: *The Pegasus*).

In the Harry Potter tales or the J.R.R. Tolkien epic *The Lord of The Rings*, cloaking and/or invisibility was left to the world of magic or mysticism. This eliminated the need for an explanation of how the cloaks worked. Interestingly, in both instances, the cloaking devices were actually cloaks; I wonder if this was the genesis of the term "cloaking device?" On the other end of the scale, *Star Trek*, like H.G. Wells' invisible man, placed cloaking in the realm of science, using engineering or chemistry to manipulate light. The cloaks of *Star Trek* are engineering marvels, requiring tremendous amounts of energy to render a ship invisible to most, if not all, electromagnetic radiation sensors. In the first season of the original series the cloak is described as an energy field projected through the deflector array, explaining why many ships could not cloak and raise shields simultaneously. In the cloak's earliest appearance in *Star Trek* (*TOS*: *Balance of Terror*), Spock speculates that *if* the enormous power demands could be met, "It is possible that a ship could become invisible." It was a only theoretical technology right up to the time that the Federation first encountered it in a Romulan vessel.

Because cloaking is not a Federation tool, the captains of the various Enterprise or Voyager vessels do not delve deep into an explanation of how they work. The entire franchise is thin on the technical details of the cloaks, it is never revealed to the viewer whether they are particulate or wave energy, or how that energy is generated. It may be that the information was never crucial to a story line, so the writers did not broach the subject, or perhaps a plausible explanation was not readily available. This is in direct contrast to 21st century Earth, where the internet is rife with comparisons of shielding devices to *Star Trek* cloaks. Some "cloaks" use mirrors or cameras and projectors, although these can hardly be considered paradigm-shifting advances, they are more like optical tricks. On the other hand, there are developing technologies that can truly be called cloaks; just imagine a covering material for the Enterprise that could bend light around the star ship or even slow or stop light completely. You don't have to imagine these, they're being improved on even as you read this, but can anyone be trusted with them?

2.2 Ways to Stay Hidden

There are many ways to remain unseen, ask any customer who needs help at a department store. Hiding under a rock or in a cave isn't really becoming invisible, although it gets the job done. The problem with hiding something is that you can't use it. You can duck behind or under something so that light rays do not bounce off

you to someone else's camera or eyes, but you have to come out from hiding to do anything, and then they know you're there. It would be much preferred if you could have your equipment and yourself in a strategic position, and yet still not be seen; hiding in plain sight as it were. To go undetected in the open is much more difficult, one must; (1) make the target look like something else, or (2) make it truly invisible. Disguises make you look like something else while camouflage makes you blend into the background, and yet these primitive, passive types of hiding in plain sight often work just fine.

Star Trek loved disguises and costumes; in many cases, Spock's ears are the main problem (*Star Trek IV: The Voyage Home*), while in others the replicator supplies the away team with Fedoras and tommy guns to help them fit in (*TOS: A Piece of the Action*). The shape shifters that play a role in several series and movies (*ENT: Broken Bow; TOS Whom Gods Destroy; TNG Journey's End; DS9: Things Past; Star Trek VI: The Undiscovered Country*) are basically disguising themselves as well, using neural and physiologic powers to look like something or someone else. They are using their talents to blend in by they are taking on the characteristics of an individual, not an area or environment, so they are still disguises, not camouflage and certainly not cloaks.

Camouflage isn't exactly cloaking either, but it lives in the same neighborhood. The differences between the two lie in the method of making something invisible in its environment, and whether the same technique can still work if the background changes. Seamless adjustment of camouflage with a changing observer, background, or light source position is tough. Shadows can easily give a camouflaged target away, and this is especially true for targets with sharp edges. Cloaking on the other hand, is the most technologically advanced form of camouflage in that can account for changes in environment that traditional camouflage cannot. In between these two extremes lies active camouflage, something well represented in *Star Trek* and a technique making its presence known on Earth as well.

2.2.1 *Active Camouflage in* Star Trek *and on Earth*

Active camouflage is much more techie then painting a tank green or a sniper wearing a ghillie suit that looks like grass. Active camouflage is beginning to develop some features that can hide things in plain sight by responding as the background changes or by helping the target take on a different disguise in real time. It's still not cloaking, although it's getting closer. It is called active because it requires an energy input, be it electrical, mechanical, or biochemical energy. In nature, many animals can change their color, with the cephalopods (squid, octopods, cuttlefish) being the kings of active camouflage (Box 2.1). The energy requirement is constant, for their skin is always being held in one pattern or moved to another, but the energy demand is not too great since they are equally willing to rest on different substrates that require vastly different camouflage patterning (Allen et al. 2010). Perhaps the largest power drain associated with their camouflage system was the

evolutionary energy it took to develop those huge eyes. They are much more developed than any other invertebrate animal because good sight and an advanced neural system are crucial to detecting the background and then matching it.

Box 2.1 Camouflage in Nature

Disguises—The crab spider of South America feeds mostly on turtle ants. In order to infiltrate the colony and find more victims, the spider wears the corpse of its last victim on its back so that they other ants will believe the spider is just another ant. A slightly different mechanism, but with the same effect is used by decorator crabs. They stick plants or mostly sedentary animals to their shells to disguise them as they hunt.

Coloration—Birds are often dark on top and light on their bellies. Hunters looking up see light color that blends into the sky while predatory birds diving from above see dark colors that blend in with the ground. Many fish use this technique in reverse.

Mimicry—Leaf insects and stick insects have varied appearances from species to species, depending on the types of plants they live on. Evolution has picked their color as well as their surface texture. The rears of some insects look like a face, so a predator doesn't know which end to attack, while many moths and butterflies have huge eye patterns on their wings. Scarlet king snakes mimic the coloration of coral snakes to make other animals believe they are venomous.

Exact mimicry is not always the best option. Zebra stripes don't mimic their environment; they don't live in a field of football referees. Yet the black and white stripes work for them because the lines look like tall grass, they break up the zebra's outline, and their main predator, the lion, is colorblind. Also, many zebras standing close together will meld stripes together, so a predator will see them as one huge striped mass, it can't pick out a single zebra to attack.

Active (energy requiring) camouflage—Many cephalopods (octopods, cuttlefish, and squids) have layers of different cells in their skin. One layer (chromatophores) can pump more pigment in and out of cells at a moment's notice, another layer (iridiophores) acts as tiny mirrors that can be angled at different directions to reflect light in different ways. A third layer has thousands of small muscles to help the cephalopod change the texture of its skin (Fishman et al. 2015). Some cephalopods have another layer of cells in the epidermis called photophores that produce light via a chemical reaction. The photophores on their bellies produce light to mimic the light filtering down from the surface.

The importance of natural models of active camouflage has not been lost on science. By studying life everywhere on the planet, models to solve engineering problems can be found and mimicked, and predictions about life on other planets can be made. On Earth we call scientists who do this work exobiologists (exo-meaning

beyond earth). *Star Trek* is aware of this and wrote the development of active camouflage into the franchise. In the *Voyager* series, it is the exobiologists Magnus and Erin Hansen who develop bio-dampeners for active camouflage. These are energy requiring and environment sensing systems that project a field around a human's body to mimic that of a Borg drone (*VOY: Dark Frontier*). They give off the proper signals and those signals change as the Borg adapts while at the same time hiding any biologic signals given off by the human body. A crew member wearing the bio-dampener could move around in the Borg Cube for hours without being detected as a foreign body.

Back here on Earth, many governments are interested in active camouflage. One example of an active camouflage method that will soon be translated to the battlefield is called Adaptiv. This battle system helps make the point that active camouflage requires a sensing system, like the eyes of a cephalopod, that passive camouflage does not. Adaptiv is a camouflage system that detects and projects an infrared signal, not visible light; therefore, it has sensors that detect the heat signature of the environment surrounding the target to be camouflaged (Fig. 2.1). Hexagonal panels mounted to sides of a tank or personnel carrier generate heat to both match the background and to disguise the heat signature of the target. Because there are nearly 1000 plates per side, patterns of heat generation can be programmed into the system, with some panels being heated, some cooled and some left at ambient temperature. Depending on the pattern selected from the system's "library," the heat signature can be camouflaged to appear as a truck, or a station wagon, or to mimic the foliage behind it. The first prototypes of Adaptiv were demonstrated in 2011 by BAE Systems (London, UK) after they were commissioned to develop just such a system by the Swedish Defence Material Administration, although they have yet to be deployed in the field.

Active camouflage points out three issues that will need to be addressed in cloaking. One, cloaking needs to allow the target to view the outside area—a

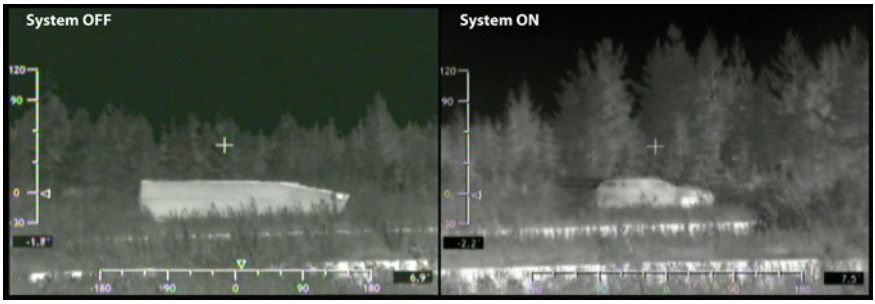


Fig. 2.1 In the *left image*, the Adaptiv System of active camouflage has not been activated, so the heat radiated by the vehicle gives away its presence and shape in a thermal image. The *right image* shows a preprogrammed pattern of heating and cooling of the side panels to make a portion of the vehicle look like an SUV, while the rest of the vehicle matches the heat signature of the background and blends in. (*Image credit* BAE Systems plc)

blinded piece of equipment is of no use. Two, the target signal needs to blend into the environment; a completely eliminated signal will look like a black hole and will be investigated. And three, the cloak needs to respond to changes and make the target hidden from observers no matter where they are or how they might change position. Several advances in optical camouflage are trying to address these issues, but remember—they aren't true cloaking either.

2.2.2 *Mirrors and Rochester Cloaks*

Certain types of optical camouflage have been hailed in the media as cloaking devices; a typical media ploy to stir up interest and readership. They are optical tricks that one can play with to simulate a true cloak and they *are* fun—unless you really need to protect yourself from a moving enemy, then they are worse than useless. All fall short of true cloaking because they require static and specific positioning of both the observer and the target. Take, for instance, two sets of mirrors that reflect light from behind an object first out to the side and then to the front. This light is then reflected back to a mirror positioned directly in front of the object to be hidden so that the light rays from behind again travel forward in their original position and direction. It works well as long as you place the mirrors precisely, hide the side mirrors well, and forbid the observer or target object to move. This is a magician's trick, not a technology.

A more sophisticated trick uses lenses instead of mirrors. Developed at the University of Rochester in 2014 by Joseph S. Choi and John C. Howell, the Rochester Cloak uses the focusing of light to create a visual dead space where an object might be hidden (Fig. 2.2). The distance needed to focus all the rays traveling through a lens to a point (the focal point) is called the focal length. In this

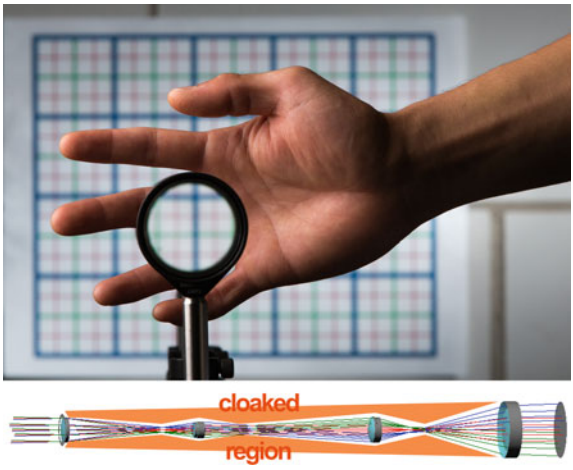


Fig. 2.2 The Rochester cloak uses a series of lens to focus reflected waves so that the region they occupy is smaller than if they traveled in a straight line. Around the center of the beam is an area that is hidden (orange region) as long as the observer views the background from no more than 15° away from the central axis of the lenses. Part of the hand seems to disappear, as long as the fingers do not interrupt the central beam. That is why he has his fingers spread. [*Image credit* (Choi and Howell 2014)]

optical trick, a series of lens of specific focal lengths are set in line on a rail, with very specific distances between each of the lenses, as determined by the focal lengths and the difference between those focal lengths (Choi and Howell 2014). Basically, light bouncing off objects in the background will be focused by the lenses with the rays of the beam compressed into a smaller cone of space as they approach the focal point, held in smaller volume between the middle lenses, and then expanded back to a larger size.

An object placed outside the constricted rays but inside the circumference of the lenses will seem to disappear if and only if the observer is looking straight through the line of all four lenses (or within 15° of that central axis). Nothing to be cloaked can impinge on the constricted cone of light being transmitted from behind the device; this is why demonstrations are often carried out with the human hand. The gap between fingers can be used to allow passage of the constricted cone of light rays, making it appear as if the entire space is cloaked. As with the mirror example above, light can be moved around an object if one adheres to the stiff restrictions on the placement of the object and the observer in order for the effect to be observed. A true cloak has no such limitations.

2.2.3 Stealth Technologies as Cloaks

Stealth technology, as used in the military, can be seen as the union of primitive deflector techniques (Chap. 4) and primitive cloaking techniques to produce an advanced active camouflage by redirecting radar signals. Radar (**RA**dio **D**etection **A**nd **R**anging) is a means by which radio waves (microwaves really) are emitted from a source, bounce off of a target, and are collected back at the source. The direction, timing, and modulation of returned radio waves provide clues as to the shape (identity), location, and movement of a target. The purpose of stealth technology is to make an airplane, ship, or other vessel less visible to radar by greatly reducing backscatter of signal from emitter back to sensor. When radar waves hit a surface, they bounce off in many directions (scattering), with only some of them bouncing back to the source to be detected. If surfaces can be designed to reduce the number of waves bouncing directly back to the collector, either by absorbing them on the surface or directing them in directions other than pure reflection, then the vessel's signal profile will be reduced.

The two most common ways to reduce a ship's radar cross section (how detectable it is) are by making the angles where surfaces meet more acute and by reducing the number of rounded surfaces that would bounce at least some signal back toward the source. Very flat surfaces tend to reflect the radio waves forward (forward scatter) or sideways (side scatter). The sharp angles also help turn the waves away from their original vector. In contrast to this, a rounded surface like a traditional plane fuselage is likely to scatter waves at all angles, including straight back to the detector. In addition to using geometry to reduce backscatter, there are paints that can absorb some of the radio waves and prevent their return to the detector. The most often used

paint contains small iron or ferrite spheres covered in quartz as an insulator. The spheres are suspended in a two-part epoxy liquid paint. After application a magnetic field is applied which spreads out the spheres evenly along the field lines, improving their performance. Microwave radar waves striking the surface are absorbed by the quartz insulation, converted to heat, and dissipated across the entire surface. More recently developed paints include multiwall carbon nanotubes (Box 3.4) instead of iron miniballs. The nanotubes are very good at absorbing energy in the microwave range, so they return an even smaller signal back to the detector.

More advanced stealth technologies are under investigation but have not been deployed yet. These would include a plasma (ionized gas, see Box 4.2) stealth shield, much like the plasma deflectors discussed in Sect. 4.4.3 and 4.5.4 for protection of astronauts against cosmic radiation, although here the plasma would absorb and deflect radar energy impinging on the plane's surfaces. This is very high tech, yet perhaps the most *Star Trek*-like stealth technology is the split ring resonator. Printed on a sheet of dielectric material, small copper C-rings have an opening that can be affixed to the surfaces of planes or ships (Abdalla and Hu 2012). The split rings allow microwave energy to enter, with the gap distance tuned to become a capacitor. Each gap width is specific for a different frequency of microwave energy, so varying the size of the rings randomly can make it active over several frequencies. Since the energy becomes stored in the capacitor-like split ring, none (or at least significantly less) is available to reflect off the surface and return to the detector. The use of a conductor with a dielectric to produce this material with unique electromagnetic qualities makes the split ring resonator a type of *metamaterial*, which will become very important as we talk below about designing true cloaks.

2.3 Cloaking the *Star Trek* Way

The optical tricks and radar evaders described in the previous sections are predicated on the idea that light travels in a straight line, it might bounce at an angle when reflected or bend (refract) as it enters a new medium, but it always travels in a straight line. The question is—does it have to? What if we could make light obey commands to bend around an object, so that no light bounces off the object at all? For true cloaks, the aim is to allow waves of EM energy to interact with a device so that the wave front impinging on a target from any direction travels on, uninterrupted by the object being hidden—the cloaked object simply doesn't disturb EM field in any way. This is a much more difficult goal. True cloaking is a sort of stealth camouflage taken to its most amazing end. Instead of hiding the object by scattering a projected beam so that it won't find its way back to a sensor, true cloaking erases an object from the perceivable universe while allowing all interactions of other objects to remain observable—one can see without being seen. This is how cloaks behave in *Star Trek*. A cloaked ship can watch, plan and ready itself, while it rests reasonably assured that nothing can detect its presence. The Klingons are especially good at making use of cloaks, although they didn't develop them originally.

Box 2.2 Basic Geometric Optics
If you look at a green glass bottle of soda, you will witness many of the characteristics of optics:

Reflection—You look closely and you can see yourself.

Absorption—If you leave it in the sunlight, it will warm up because some light is held by the glass and the energy is converted to heat.

Transmission—The bottle is a solid object, but you can see how much soda is left, so some light waves pass through the glass.

Refraction—The level of soda inside is altered slight from where it actually is because light passing through the glass is bent slightly as it enters and bent back as it leaves. Different materials have different indices of refraction and the value can be altered by temperature, wavelength of the incident light, and density of the medium. The reason for the bend is due to something called phase velocity, where the speed of the peaks of the light wave will seem to travel slower in more refractive materials. To maintain a constant speed of light, it must bend to accommodate the peaks slowing down. More refractive materials have slower phase velocities. Diamond bends light a lot (has a high refractive index). This is why diamonds sparkle so much. Water has a low index of refraction; this is why the stick you fiddle with in the water looks slightly bent where it enters.

Scattering—You can see the bottle, so light waves strike the bottle, bounce off in several directions and some of those scattered rays travel to your eyes. The green light is reflected and scattered more, while other frequencies are absorbed. This is why the bottle appears green. Different materials absorb different wavelengths of light, longer wavelengths are the reds, and the wavelengths get shorter and higher energy as you travel from red through orange, yellow, green, blue, indigo and violet (ROY G. BIV). The same thing happens outside the visible range of electromagnetism, but we don't see it.

For reflected and scattered light, angle of incidence equals angle of reflection. If the surface isn't perfectly smooth, then some of the light will be reflected at many angles; this is scattering. You can see a searchlight beam directed into the sky at night because some of the rays (waves) are scattered by particles in the air and even the air molecules themselves; some rays are scattered toward your eyes and you see the beam. Scattering by molecules (things smaller than the wavelength of the incident light) directs rays in all directions.

The Klingons received cloaking technology from the Romulans during their brief alliance, so all the early cloaks probably operate on the same principle, an energy field projected through the deflector array (*TOS: The Enterprise Incident*).

Romulan cloaks are made of a tetryon compositor and a projection matrix—neither of these is explained fully, although tetryons are supposedly a type of subspace particle (*DS9: The Die is Cast*). Fortunately, space station Deep Space Nine can detect tetryons particles, so Romulan cloaks probably aren't much good in the 24th century. This may be why Romulans develop cloaks with different actions, with at least one based a prismatic mechanism (*TOS: The Enterprise Incident*). In the *Enterprise* series, the Suliban receive cloaking technology as a gift from an unknown benefactor in the 28th century (*ENT: Broken Bow*). It works differently from the Romulan cloaks, as it is based on a particulate substance, as witnessed by engineer Trip Tucker spilling some of the Suliban particles on his hand and arm, rendering them invisible for some time (*ENT: The Communicator*).

Using any of these cloaking techniques, planets (*TNG: When the Bough Breaks*), ships, minefields (*ENT: Minefield*; *DS9: Call to Arms*), even individuals (*Star Trek: Insurrection*) can be hidden from prying eyes. They also happen to be undetectable to heat, microwave, gamma ray, or most other wave or particle radiation emission sensors; true cloaks work over the entire EM spectrum. It is true that some cloaks have weaknesses that can be exploited where some exotic particle or energy trace can be detected, like the "quantum beacon" used to locate a cloaked a minefield (*ENT: Shockwave*). These weaknesses set up a back and forth cloaking/detection race that is so familiar to the arms races we have seen in the recent past. In this case, the Klingon ships show up in short order with a new cloak on which the quantum beacon is ineffective (*ENT: Minefield*). As Spock says, "Military secrets are always the most fleeting." (*TOS: The Enterprise Incident*).

2.4 Cloaking by Bending Light

Commander Spock notes in *Balance of Terror* that while it might be theoretically possible to selectively bend light around an object, it would take a tremendous amount of energy. Well, he was wrong on both counts. Cloaking is more than theoretically possible; cloaks that can obscure objects from specific portions of the EM spectrum exist today. And while broad band cloaks may require an input of energy, some recently demonstrated cloaks are completely passive; light strikes them and they, and the object they are surrounding, just disappear. And while Spock ponders the possibilities of cloaks in the 23rd century, cloaking actually has its scientific genesis in the 20th century mind of Albert Einstein, by way of two British geniuses—James Clerk Maxwell (1831–1879) of Scotland and Sir John Pendry (1943–) of Imperial College, London. Using the knowledge of optics that these giants gave us, the cloaking techniques that exist as of 2015 fall into two broad categories—EM wave bending and EM wave scattering suppression. Since Spock contemplated light bending, we will first look at how Einstein, Maxwell, and Pendry have taught us to move light around an object.

2.4.1 Transformation Optics

Einstein considered space, light, gravity, and time as interconnected. He proposed that if you distort space with a large mass (like a sheet being deformed by a ball placed on its surface), and then shine a light beam through that distorted space, it will bend around the mass instead of traveling in a straight line. Maxwell had earlier developed the mathematical equations for the behavior of electromagnetic waves in free space, and Einstein used these to formalize the behavior of electromagnetism in his curved space. This part of his theory of general relativity was proven correct in 1919 (Sect. 4.2.4). Jump forward to the 1990s when Dr. Pendry wonders about the implications of the reverse situation. If light bends in distorted space, what would space do in the presence of distorted (bent) light?

The fact that electromagnetic radiation travels in straight lines makes it tough to bend light around a body, allowing an observer to see what is directly behind it. However, light does bend as it passes from one medium to another, like air to water or air to glass. When light hits an object, it may bounce off in many directions. Sometimes the light is reflected off of an object's surface and returns back in the direction from which it came, while other rays may be scattered at some angle from the surface. If light can pass through the medium, then it may be bent at a certain angle (called refracted) based on the material it is entering and the wavelength of the light itself (Fig. 2.3). However, in all these cases (reflection, scattering,

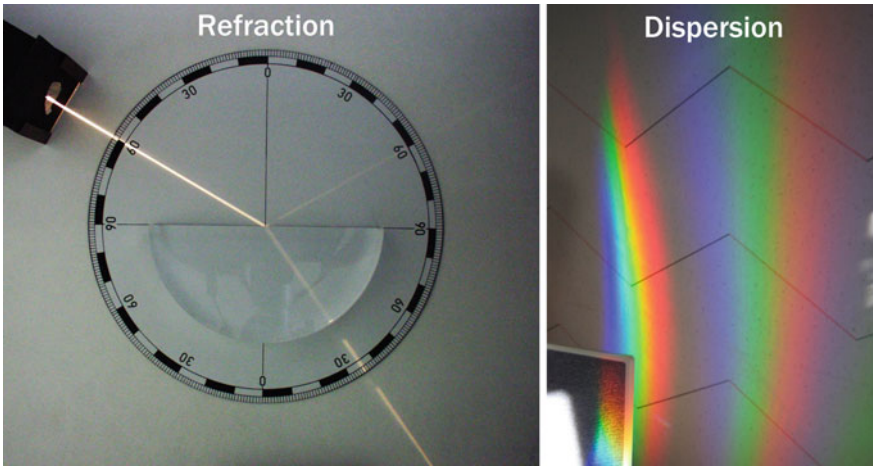


Fig. 2.3 Light shown through the plastic of a protractor bends due to the plastic's index of refraction. The angle of incidence equals the angle of reflection for reflected rays, but the transmitted waves bend by some 25°. The index of refraction is dependent on the wavelength of light (amongst other things), so white light containing all colors will be refracted to different degrees (dispersed), spreading the individual frequencies (*colors*) out over a distance. (*Image credit for refraction* By Zátonyi Sándor (ifj.) Fizped (Own work) CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0), via Wikimedia Commons, the image has been merged and labeled) (*Image credit for dispersion* By no machine-readable author provided. Andreas Rejbrand assumed (based on copyright claims). [GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons)

transmission and refraction) the light wave is still traveling in a straight line. It is the straight line movement of light that allows us to locate objects in our field of vision. Light from a source strikes the object, and some of those rays bounce off and travel to our eye. If they didn't travel in a straight line, how would we know where the object was?

Consider the case where a hot blacktop road heats the air directly above it. Temperature affects index of refraction (how much it will bend light as it enters the new medium) so the different layers of air above and beside the road will bend light to different degrees. As the light waves that bounce of a palm tree in the distance and travel through volumes of air with different temperatures, they are bent, then bent more, and then bent back. The result is a wavy image that can't quite be placed at one specific location. Philip Ball's 2015 book, *Invisible: The Dangerous Allure of The Unseen*, explains nicely how light bends (refracts) when entering a different medium because it is looking for the shortest time of passage. Light in a vacuum travels at 299,792 km/sec (186,000 miles/sec), but in other media one aspect of light (phase velocity) slows a bit. In order to traverse the new medium in the same time as it would in a vacuum, it must take a shorter path, so it bends. For each material the degree of bend is slightly different, therefore every transparent substance has a unique index of refraction, which is also influenced by temperature, density and the wavelength of the light.

What Dr. Pendry realized was that the bending of light to distort space is mathematically equal to changing the index of refraction over a distance. Theoretically, one could bend light to distort space just as easily as distorted space can bend light. His conclusion: if you bent the light sufficiently, you could move it around an object just as water moves around a rock in a stream, rejoining the rest of the water on the other side as if the rock had not been there. The bending of light would be the moral equivalent of folding space into a tiny volume so the light could pass right by unscattered. Maxwell's equations could be modified to tell you how much to change the index and at what positions. This wasn't just a mental exercise for Dr. Pendry, he told me that an attempt to make something disappear was a, "grand challenge; something to capture the imagination of the public."

This was the birth of the new field of transformation optics, where "optics" describes the study of how light moves through a medium. The problem was that the equations called for a material with unique properties of bending light, properties that don't exist in many (or any) natural substances. Instead of slowing down light and therefore causing it to bend a certain degree, a cloak might require a material to speed up light at some spots and slow it down in others. Speeding up and slowing down light in this instance is a matter of looking at the different components of the light. The speed of a single part of the wave, like all the peaks, is called the phase velocity, while the propagation of the light wave as a whole is called the group velocity (Box 2.3). The movement of light into and out of a medium alters the phase velocity, and this is why it bends to take a shorter path. By taking the shorter path, the group velocity can be maintained at the universal constant speed of light. Or is it a constant? We shall see later that this constant isn't so constant, and might be used as a cloaking technique (Sect. 2.6.2).

Natural materials have indices of refraction between 1.0002 for air and a whopping 4.05 for germanium. Diamond has a high index of refraction (2.417) while liquid helium hardly bends light at all (1.025). What science needed for bending light and distorting space was a material that could be designed to have arbitrary indices of refraction at different points in space, and together these would manipulate the light direction and speed as it traveled around an object. Importantly, the material of the cloak would have to have a different index of refraction for rays of light that strike it from different directions, a property called anisotropy. You've seen the effects of anisotropy many times (Fig. 2.4). Birefringent butterfly wings that change color depending on your position relative to them and automobile paints that shine purple to green or blue are examples of anisotropy. Since each frequency of the EM spectrum reacts differently to a material's index of refraction, white light and sunlight will be dispersed (scattered) differently because it is made up of many

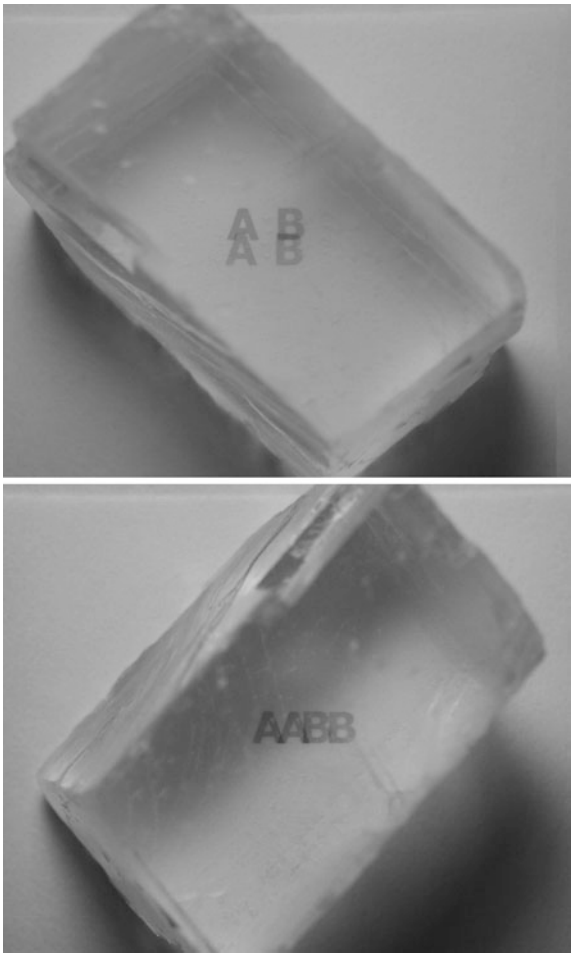


Fig. 2.4 Calcite crystals are anisotropic. Light travels through in different ways based on the angle of the material to the light. The anisotropy produces a double refraction, where a ray of light will be split and take two different paths, each with a different index of refraction. Notice how the position of the doubled letters changes as the orientation of the crystal changes. (*Image credit*: D. Walker. *Examples of the animation of macro and microscopy subjects using sequential jpeg images*. Micscape, May, 2004)

frequencies. Looking from one direction scatters it in a particular way so that purple waves are reflected to your eye, but look from another angle, and the anisotropy determines that green waves will be scattered.

Working with Dr. Pendry on this idea, and doing his own work on changing indices of refraction, was Dr. David Smith of San Diego. Dr. Smith explained to me that the importance of anisotropy in transformation optics is hard to visualize; suffice it to say that it is crucial because the math says so. In transforming space, some areas get squeezed and others stretched changing the relative direction from which light is striking the material. Therefore, being able to modulate light from different directions in the distorted space becomes necessary (Smith, personal communication). Dr. Smith had found a way to make extremely small copper wires behave exotically with respect to microwaves by giving them specific shapes and diameters. A chance meeting between he and Pendry led to a discussion of printing small copper wires on a surface to produce a material that could do even more—change the material's index of refraction. Because light is electromagnetic radiation, it has both an electric field and a magnetic field. The embedded copper wires changed the *permittivity* of the material (how much it responds to the electrical field of light), but a C shaped ring of the wire also altered the material's magnetic *permeability* (the degree to which a substance responds to light's magnetic field). Together, the permittivity and permeability determine a material's index of refraction, so manmade materials with specifically designed permittivities and permeabilities can alter light's direction and speed in predictable ways.

2.4.2 Gradient Index Metamaterial Cloaks and Their Limitations

These manmade materials were already known by this time and had been named *metamaterials*, although they had not yet been used for this novel purpose. In 2006, Smith (Schurig et al. 2006) and (Pendry et al. 2006) both published papers wherein they demonstrated similar methods to hide a volume of space from a narrow band of microwaves. The invisibility device itself, and anything held within the center of its concentric circles of metamaterial, looked as though it wasn't there when a beam of microwaves was sent across its path and sensed by a detector on the other side—a true cloaking device. This was a seminal moment for Dr. Smith, who had grown up a *Star Trek* fan and had a scene about cloaks from the original series playing constantly in his head as he contemplated the possibilities of cloaking (Smith, personal communication). Actualizing a piece of *Star Trek* technology was a very big deal to this particular trekkie.

For the transformation optics cloaks of 2006, each of ten concentric circles of the metamaterial bent the light a specific amount so that it would curve around the object and then back to its original path (Fig. 2.5). The equations of transformation optics designated what change in index was needed for each ring, creating a gradient of

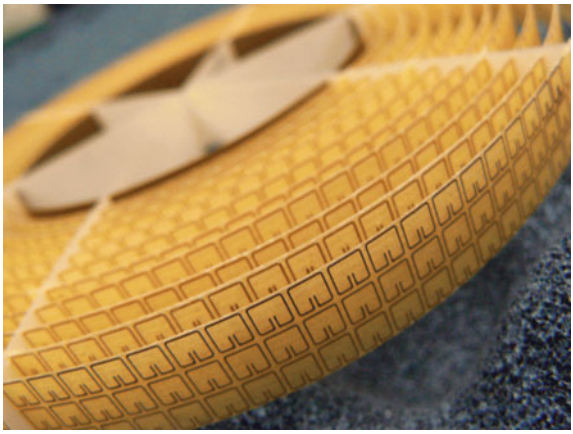


Fig. 2.5 This is one of the first gradient index cloaks to hide space from EM radiation. Light passes around the cloak through the various layers of metamaterial that have unique abilities to bend light. The combination of the copper wire and translucent material in each repeating unit cell determines the index of refraction, and the shape of the unit cells changes from ring to ring; this produces the correct overall bend. (*Photograph credit* Dr. David Schurig)

indices of refractions. Therefore, this is called a gradient index cloak, or more generally, a transformation optics cloak. The light traveling through the cloak was seemingly sped up and then slowed down by changing refraction, yet they arrived at the front of the cloak at the same time as all the waves that did not travel through the cloak (were above or below it or off to one side or the other). The mathematical distortion of space to a point meant that it was just as if all the waves traveled in a straight path to the observer. This maintenance of a common wave front is important for a cloak; only in this way will the background remain uninterrupted and no edges be detected where some waves went through the cloak and others didn't. Press releases heralded the age of invisibility cloak, despite the obvious problems that need to be overcome—and there are many. Scientists and the military use extended parts of the EM spectrum for emission and detection, but for most of us, we know something is there because we see it with our eyes, making use of only visible light. Because of this bias, the public wants a cloak in the visible light range, yet no current gradient index cloak can work in visible light, most work in the infrared or microwave range.

For materials with large crystalline structure, light takes an "average" of the material's optical properties and develops a behavior based on this. For subwavelength materials, like metamaterials, the light wavelength is actually larger than the unit cell (sometimes by an factor of 1000), and this keeps the waves from "seeing" the material. Light doesn't scatter off a metamaterial with the complexity that it does off natural materials, and this simplicity makes the light easier to manipulate, as long as the wavelengths are relatively long. Visible light waves are about 20,000 times shorter that microwaves used for radar and most gradient cloaks. To be able to manipulate visible light as needed for cloaking, the unit cells will have to have much smaller, and this is harder to manufacture. This is a problem, but it isn't the only problem with moving cloaks into the visible range. Metamaterials also need to keep the electrons moving with certain properties. As the wavelength gets shorter, the electrons in the metamaterial must speed up more and more to maintain the same movements. More speed from the electrons means more distortion, and this

makes the cloak itself visible and less effective for hiding objects (Pendry, personal communication).

Another problem to solve before transformation optics cloaks will achieve *Star Trek*-like invisibility is that index gradient cloaks have the unfortunate side effect of blinding the cloaked object from the outside world. The cloaks work by bending light around the object instead of letting it reach the surface and be reflected or scattered. Just like how no light reaches your retina and you see nothing when you close your eyes, a gradient index cloaked target's sensors receive no incoming light; therefore, the crew can't see anything going on around the ship. How will the commander know when it is safe to decloak or where or when to fire? Starships in *Star Trek* can still see space and the objects in it while cloaked, so this is a severe limitation that must be overcome.

Finally, there is the issue of effective limited bandwidth that must be solved. Each wavelength of light has a specific phase velocity change as it enters a new medium (aka—a different index of refraction). Metamaterials are designed with very specific indices of refraction, so if you shine light of many different wavelengths on a cloak, they bend to different degrees (called dispersion) and do not all follow the path described by the equations for that particular cloak. A rainbow is a good example of this dispersion of wavelengths. As white light passes through a droplet of water, the different colors of light (based on their wavelength) are refracted differently. As the waves pass through many droplets, the dispersion increases, so that you eventually see the different colors distinctly, each based on how far they refract, and each refraction based on the wavelength, with red light refracting most and violet light refracting least. The order always ends up the same; red, orange, yellow, green, blue indigo, violet. The same thing happens across the entire EM spectrum, we just don't perceive it with our eyes. Therefore, gradient index cloaks are necessarily functional over a very narrow bandwidth to reduce dispersion. If a wider band is used, some of the waves will disperse and cause a shadow, making the cloak itself will be detectable. Science fiction cloaks seem to work over very wide bands; second generation Romulan cloaks hide ships or other objects from *all* EM waves. Dr. Smith has a way to go before he realizes a *Star Trek* cloak that matches that of the Romulans.

Box 2.3 Cloaks Of All Sorts

Anything that travels as a wave, pressure, sound maybe even heat, can theoretically be cloaked. Examples include:

Acoustic cloaks—Sound travels as mechanical waves and travels well in water, and is the basis of sonar detection of ships and submarines. A cloak developed at Duke University might uses metamaterials on the hull that modulate acoustic properties and have precisely sized holes drilled in them based on wavelengths of sound to be masked. The cloak returns a signal of exactly the same type that was sent, suggesting that no metallic object reflected the wave (Zigoneanu et al. 2014). There are possible uses for the

acoustic cloak in air as well, such as reducing echoes and giving people in the cheap seats a decent chance to hear the music at the symphony.

Earthquake cloaks—Two different methods being tested to reduce the physical and financial damage of earthquakes. One method places rubber stressed in particular directions *around but not touching* the foundation, and this stress deflects seismic waves away from the building (Parnell 2012). A second type of earthquake cloak modifies the soil around the building to deflect and absorb seismic waves. To do this, scientists are developing seismic metamaterials that alter the soil density and soil's elastic modulus, just like gradient index or metascreen metamaterials alter optical properties. In early tests, simply drilling strategic holes in the soil reduced the force of seismic waves encountered by a target by 80 % (Brule et al. 2014).

Mechanical cloaks—It may be possible to cloak the pressure you feel from an object when you touch it. Some types of metamaterials exhibit unique physical properties that redirect pressure to a flat surface around any object that fitted inside the cloak (Buckmann et al. 2014). Nanometer sized cones in the cloak have tips that bend and meet with precisely designed forces generated. Using an inversion of the mathematical equations for optical properties, solids can be designed to be stiff in one direction, but shear easily in another, or vice versa.

Temporal Cloaks—Metamaterials can be used to hide events in time as well. A beam of light can be sped up in a metamaterial so that it reaches a point before an event takes place. The light behind it can be slowed down, so that by the time it reaches the same point, the event has already occurred. The sped up portion can then be slowed down and the slowed down waves can be sped up, so the wave front arrives at an observers eyes without disruption, yet lacking a recording of the event that occurred in the middle. This technique has been demonstrated (Fridman et al. 2012) and may first play a role in secure data transmission (Lukens et al. 2014).

Make no mistake—the gradient index instruments are true cloaks; objects are being hidden from light waves. What is more, they will only get better with time. For example, transformation optics equations yield results that are hard to reproduce in materials, so approximations must be made. This reduces the effectiveness of the cloak or limits the directionality and dimension in which it will work; fortunately, the number of approximations is being reduced all the time. Dr. Smith and his colleague Nathan Landy published a demonstration of a microwave cloak (Landy and Smith 2013) that used no approximations to the transformation optics equations and yielded an effective cloak over a larger range of wavelengths. However, to widen the range they had to limit the number of dimensions (X/Y) that it would work in and limit the source light to coming from one direction. The math involved in creating a

wide band cloak that functions with light from any direction and can cloak a spherical space (X, Y, and Z dimensions) is harder to reproduce without making shortcuts and materials to produce such a cloak are harder to manufacture. Once again, nature comes to the rescue. Natural materials are giving scientists clues how to build transparent cloaks and cloaks that work with visible light.

2.4.3 Natural Calcite Carpet Cloaks

In general, making cloaks work in three dimensions means that one must account for light scattering in more directions. Limiting the dimensions in which the cloak acts simplifies the math and reduces the approximations. The first metamaterial microwave cloaks were produced as flat surface and then curved to produce a cylinder, giving a cloak in the X and Y dimensions only. This is much easier than trying to produce the unit geometry on a spherical form, although the object would not be cloaked from microwaves that shone on it from below or above the plane of the cylinder. The math of a spherical cloak produces a wire shape—a hard area to hide, but calculating the compression of space by a cylindrical cloak reduces the volume inside to a single point. Even easier to produce and predict than a cylinder is a flat sheet cloak, a so-called carpet cloak (Li and Pendry 2008). Natural crystals have been manipulated to produce decent carpet cloaks, and some even work in the visible range, an impossibility for present index gradient cloaks because of the smaller units cells required.

Natural calcite (calcium carbonate, $CaCO_3$) crystals are an example of a cloaking material functional in the visible spectrum. Small prisms of the crystal are attached to one another as a flexible, two-dimensional surface. Anything placed under the cloak, even a ball under a carpet that deforms the surface, will have its reflected light refracted in many arbitrary directions. The light passes through the cloak, bounces of the target object and some of that light bounces back through the crystalline cloak again. All the combined reflection and refraction means that little of the light reflected from ball will return to the eye, and even less will be returned in a manner that shows the shape of the object. Instead, the light of the background will overwhelm all other patterns and the cloak will blend in perfectly. Granted, the object must be laid on a mirrored surface to ensure that all the refracted light will be bounced through the prisms, but it allows for the target under the carpet cloak to disappear. This is one way to achieve cloaking in the visible range, and even though it comes with limitations, it is actively being pursued by the military.

Meshed crystal prisms are not the only way that calcite can be used as a carpet cloak. If you have two larger crystal prisms lined up back to back, the natural optical effects of the crystals can break up the light enough to hide an object placed in a void beneath them. Despite calcite being transparent, the light is broken up as it passes through the crystal because it is anisotropic and double refracting (birefringent, see Fig. 2.4). The carbonate ions are arranged in flat sheets, so light perpendicular will be affected differently than light that enters parallel to the sheets.

Calcite breaks an entering light beam into two rays that have different indices of refraction and therefore take different paths. One ray, called the ordinary, is refracted according to the index of refraction for calcite. The other ray, the extraordinary, is refracted at an angle that depends on the angle at which the light strikes the crystal relative to the flat carbonate sheets. Turning a calcite crystal as it lies over printed image will produce two images, with one of the images moving around the other as the crystal is rotated. The moving image results from the extraordinary ray.

By placing calcite crystals back to back, the combination has four paths and speeds during each path through the crystal. The overall effect is similar to the flat surface described above made from many small flat crystals, although the light must be shone directly at the crystals. These dimensional optical glass cloaks have been demonstrated in the visual range by B. Zhang at MIT in 2011 (Zhang et al. 2011) and S. Zhang at the University of Birmingham (Chen et al. 2011) in recent years, hiding anything beneath them as long as they are narrower than the width of the crystals themselves. Of course, the cloaks are visible and cask shadows unless the light is polarized and the entire setup is under water (Fig. 2.6), so their use in cloaking starships in their current form is limited to say the least.

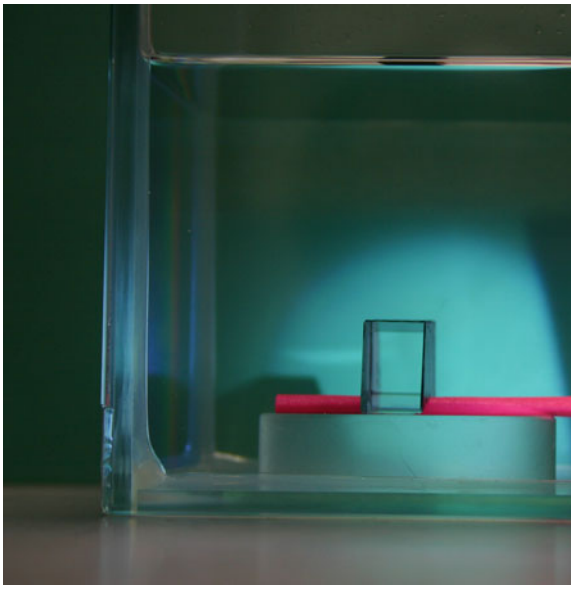


Fig. 2.6 The calcite crystals are joined back to back, each with a wedge removed at the bottom to form a central trough for hiding objects. The light rays reflected from the pink tube are bent and re-bent by the double refracting calcite. Notice that the entire apparatus is in a fish tank of water to eliminate shadows and the light is shone directly on the calcite crystal. However, that portion of the pink tube under the calcite blanket does disappear from view. (Photograph courtesy of B. Zhang and G. Barbastathis)

2.4.4 Natural Guanine Crystal Carpet Cloaks

The skin of some fish act as natural cloaks, helping them blend into the color of the water around them by perfectly reflecting the light back to the observer. Most reflectors are imperfect, they tend to polarize the light as it bounces off. The polarized light has more rays traveling in one certain direction, instead of scattering off the surface equally in all directions. The higher number of rays traveling in one direction creates a more intense light that we see as glare. Fisherman wear polarizing sunglasses to block the horizontally polarized rays and glare of the sunlight off the water, just as photographers use polarizing filters to eliminate glare caused by polarized reflected light.

For fish, reflecting the light helps conceal them, but the glare created from polarization would give them away. To combat this problem, some silvery skinned fish, like herring and sardines, have evolved a crystalline cloaking mechanism that gives high reflectivity without polarization. Engineers and researchers in optics usually overcome polarization in optical communication devices by using sophisticated filters and surfaces, with the unfortunate side effect that these lower the efficiency of the reflectors, thereby increasing the noise in the signal. By mimicking the fish system, these optical devices can be made much more efficient.

The fish don't care about optical communication, they are more worried about cloaking themselves. The system they have evolved uses multiple layers of hexagonally shaped guanine crystals to help them blend in with the water. Guanine is one of the chemical bases used in DNA and RNA. Here their function is structural, not informational; many of the small guanine crystals join together in a lattice formation to create crystals with interesting optical properties. It has been known for some time that sardine skin contains multiple layers of these crystals, with scientists assuming that the result of sunlight striking them would be full polarization—equal scattering in all directions and no glare, but also a loss of reflectivity. The truth, as reported in a recent study from the University of Bristol in the UK, is that the glare is prevented while high reflectivity of the surface is maintained (Jordan et al. 2012).

The experiments showed that the layers contain two different types of guanine crystals, each with their own optical properties, and it is the mix of the two crystals that gives the high reflectivity, no glare characteristic, similar to how the mixing of the dielectric and anisotropic solids in metamaterials achieve unique permittivities and permeabilities. However, unlike gradient index cloaks that bring the light from behind an object to the front, the carpet cloak of fish skin reflects the light that was in front of the cloaked object. If the fish swims across the front of a colorful reef, a predator would see them as a shadow against the background. This may be why this evolutionary strategy has evolved in fish that mostly in open water and are attacked from below. Looking up, the predator is much more likely to lose the fish against the uniform background.

A similar guanine system is responsible for the invisibility of a class of small crustaceans called Sapphirina copepods. These marvelous looking animals can be

iridescent in color, from fluorescent blue to gold or orange, yet by turning their body slightly they can disappear from view in an instant. The hexagonal layers of guanine crystals are very similar to those seen in fish scales, but their arrangement here dictates that when the animal turns 45° to the sun, all the reflected light shifts into the UV ranges and they disappear from sight (Gur et al. 2015). Amazingly, it was shown a few years ago that magnetic fields can alter the guanine crystal optical properties, changing the wavelength of the reflected light. By increasing the magnetic field strength from two to ten tesla, the fish scales tested changed from white-green to dark blue or violet (Iwasaka et al. 2012). This shift from lower to higher frequency light suggests that an even stronger field could shift the light into the ultraviolet spectrum. This suggests a mechanism to control a carpet cloak of guanine crystals, allowing a target object to go from iridescent to invisible on command. Metamaterial index cloaks can neither be tuned on command nor work in the visible spectrum, so there may be something to be said for following nature when designing these first generation cloaking devices.

2.5 Cloaking by Destroying Light

Bending light around an object or breaking light up so much that a cloaked object disappears in the reflections/refractions are not the only ways of cloaking that are being studied. Another class of metamaterial cloaks attack the problem from a different angle, and may be able to overcome some of the cloaking limits described above. For these cloaks, the metamaterial generates an optical signal equal and opposite to any light scattered by the target object and cancels it out. It is as if the cloaked object doesn't exist because no light reflected from it ever reaches your eye.

2.5.1 Plasmonic Cloaks

First demonstrated in 2012 (Rainwater et al. 2012), the "plasmonic" or "light-canceling" cloak is a device that is thinner than the typical gradient index cloak. Plasmonic cloaks are made from a single layer of an engineered compound that is placed around the target object with just a narrow gap between the two. The gap is essential to the functioning of the cloak, because unlike the gradient index cloak that keeps light away from what is to be hidden, the plasmonic cloak requires that incident light be scattered off the target so it can be canceled. The types and wavelengths of light scattered from a target object depend on the material it is made from and the structure of its surface. Therefore, to cancel out only the light scattered from the target, a plasmonic cloak must be designed with both the target and the wavelength of the incident light in mind. This is different from the transformation optics cloaks that can hide whatever object is placed in the cloaked region.

To achieve their goal, light-canceling cloak designs use metamaterials. However, the term metamaterial is a catchall term according to Sir John Pendry; it really encompasses many different types of materials that have unique optical properties. Plasmonic cloaking metamaterials have very different properties than those of transformation optics metamaterials, but one thing they all have in common is that they can be fabricated to have very specific optical characteristics at any given point. Which property you wish to manipulate then determines the constituent materials and geometry of the given metamaterial. Plasmonic cloaks utilize metamaterials that have very low permittivity properties; they react strongly to the electric field generated by light waves. Their electrons move around more within their molecular structure when light strikes them (high electron flux) and this has a polarization effect.

Taken together, the cloak and target work to radiate a light wave with a very specific wavelength and phase, which is designed to be the negative of the wave scattered by the cloaked object. The scattered light from the cloak is exactly that light which is 180° out of phase with the object being cloaked, so the interference between the waves scattered from the object and the waves scattered from the target causes both to be canceled. This don't just render the cloaked object invisible, it renders the cloak invisible as well. This makes a plasmonic cloak very much like Harry Potter's cape; you can see it when Harry isn't wearing it, but both the cape and Harry disappear when he puts it on. In the case of a cloaking device, if you remove either the cloak or the target inside it, then both become visible.

The cancellation of the scattered light explains why one doesn't detect the cloak or the target, yet the light coming from behind the cloak is unaccounted for. It would seem that a shadow would form, giving away the cloak. Dr. Andrea Alu of the University of Texas at Austin explained to me that the light coming from behind the cloaked object is restored by the plasmonic cloak because some of the incident light from behind can travel through the cloak unimpeded. Remember, light must be able to get to the target object within the cloak for it to work, therefore, much of the light from behind will pass straight through to the observer. If the target itself doesn't transmit, some light from behind will trickle around the surface of the object as charges called *surface plasmons*, although the name of the cloak comes from plasmons generated in the metamaterial, not the target. The surface plasmons help reestablish a front on the other side along with those that did not interact with the object or the cloak. The canceling of only scattered waves and the transmission of unimpeded waves means that you can see the background, just like with the transformation optics cloaks.

2.5.2 Mantle Cloaks

One year after introducing the plasmonic cloak, Dr. Alu and colleagues demonstrated a mantle cloak based on the similar principles (Soric et al. 2013). This cloak was much thinner (166 μm, 0.0065 in.), about as thick as a sheet of paper. They

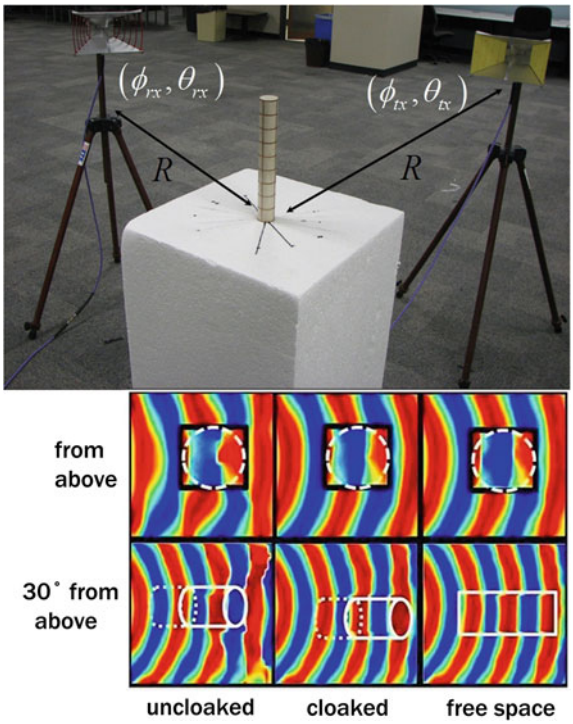


Fig. 2.7 This plasmonic metascreen cloak is only 166 μm (0.0065 in.) thick, yet can destroy reflected and scattered rays in the microwave region. The cylinder target is wrapped with the cloak in the image above, and microwave emitters and detectors are directed straight through it or from 30° above the plane. The lower images shows how the wave front is distorted in the uncloaked situations, but the cloaked versions more closely resemble the gentle curve of the wave front in free space. (*Image credit* (Soric et al. 2013) under CC BY 3.0 license (https://creativecommons.org/licenses/by/3.0/us/legalcode), portions of three figures have been merged)

termed this a metascreen, since it is mostly a transparent sheet with nanometer (one millionth of a millimeter) thick copper wires embedded in it. The advantage to this design is that the thinner the cloak or mantle, the broader the range of wavelengths it can cancel out. The metasurface, as it is sometimes called, radiates out of phase waves based on slightly different properties of the material as compared to the plasmonic cloak. Namely, it resists a flow of electrons after an incident light wave strikes it. That resistance causes the light wave to be radiated instead of propagating on the material as a surface plasmon. However, as with the plasmonic cloak, the impedance (resistance to flow) varies with the frequency of light, so these cloaks are effective over only certain bands of EM, not all bands. Alu's plasmonic and mantle cloaks were both designed to cloak within the microwave region (Fig. 2.7).

The idea of mantle cloaks has taken off in the past couple of years. Zhang and colleagues at the US Department of Energy's Lawrence Berkley National Laboratory call their metascreen a "skin cloak" (Ni et al. 2015). At only 80 nm (3.15×10^{-5} in.) thick, this cloak could easily be used to cover any three dimensional object. In Zhang's demonstration it was used to hide a space about the size of a few human cells, but the authors say it could one day be scaled up to cover macro-objects, perhaps even a Klingon or Romulan ship. Their current version is

effective at the 730 nm wavelength (infrared light) only, right on the edge of the visible range. This is a major step forward as compared to other metamaterial cloaks.

Even beyond the possibility of visible light cloaks, the principal advantage to cloaking with metascreens or plasmonic cloaks is that the cloaked object is not blind when it is hidden. Light strikes the cloaked object and can be detected by sensors on the object—whether they be the eyes of the crew or EM sensors on the ship. Either way, the captain can direct the ship more satisfactorily since he/she can see what is going on around them. Also an advantage, specific transmissions can be sent from the cloaked object, as long as they are not in the functional spectrum of the cloak, they will be broadcast just fine. Finally, the size of mantle and plasmonic cloaks is much more manageable. The width of a gradient index cloak is often double that of the object being cloaked, whereas with the metascreen it can be a thin coating held just off the surface of the ship or other target object.

On the downside, Dr. Alu laments the fact that the properties used make mantle cloaks are very sensitive to frequency. The size of the possible target goes down as the wavelength gets shorter. Since visible light has a much shorter wavelength than radio waves (on the order of a hundred million times shorter), the size of objects that could be cloaked from visible light using current mantle cloaks is in the microscopic range. This is why the skin cloak of Ni and Zhang described above was effective only for an object the size of a few cells. However, Dr. Zhang is of the opinion that the cloak could be scaled up for larger objects, since it uses nanometer sized gold nanoantennae that can be switched on or off to change their polarization, a method slightly different than that of Alu.

2.5.3 *Spoofing and Illusion Coatings with Mantle Cloaks*

Jiang and Werner of Penn State University (Jiang and Werner 2014) recently demonstrated another mantle cloak with a peculiar twist. It is a single metasurface layer similar to Alu's, but is effective on larger objects. The cloak was designed to be functional against radio waves, and it will hide objects from those wavelengths, yet it's best use may come in another area. Often, military or communication vehicles with tops that house many different antennae have interference and jamming problems because the signals of one antenna disrupt those of another. The authors of the Penn State study found a way to modulate their skin cloak's optical properties so that the hidden object would appear to be silicon instead of metal or metal instead of glass. This technique is called "spoofing," an engineering riff on the software technique of masking a website or email address as something else. In spoof cloaking, one object is cloaked in a way to make sensors detect a false signal. This is one of the areas in which Dr. Pendry sees real promise for metamaterials, and is possible because the transformation optics math that he derived allows one to design metamaterials that can manipulate the light that travels to an object, not just bend it. With a gradient cloak one can make an object look larger or smaller or change the ways it's edges are perceived, and a metascreen can change the

signature to make it appear to be another structure, including hiding one antenna from another.

Of course, *Star Trek* led the way here as well. Chief O'Brien once configured the navigational deflector (Sect. 4.2.1.1) to project a false Federation warp drive signal onto a weapon platform's generator (*DS9: Tears of the Prophets*), fooling it into firing on its own power source. This is a form of spoofing, and although O'Brien uses the deflector instead of the cloak there isn't too much of a difference. In real life, spoofing with thin mantle cloaks sometimes called "illusion coatings" could very well have significant value in the military, when troop positions may be given away by sensors trying to locate a radio-emitting antennae. Beyond the military, being able to make one antenna invisible to others will keep communications clear and allow for more co-sited devices. Perhaps most impressive, spoofing with metamaterial cloaks can make an object appear to be where it is not—a spoof in location. This is not the only way to cloak an object by changing its apparent position; we will see below that this might be done by slowing or stopping light.

2.6 Future Cloaking Possibilities

Star Trek has cloaks that hide ships and other large objects from every frequency of EM radiation. Current real life cloaks cloak small objects over small bands of the EM spectrum, although the progress described above suggests that this won't be the case for long. Not only will the capabilities of cloaks be expanded by incorporating diverse synthetic and perhaps natural materials, the uses for cloaks will grow as technology calls for shielding signals in optical computing and even in aviation or automobiles. Imagine having a 360° view from your driver's seat because the roof and sides of your car are cloaked from your point of view. Sir John Pendry sees cloaks "galloping off in all directions" in the next few decades, including thermal cloaks to protect electronics from damaging heat. He is, however, less optimistic about earthquake cloaks (Box 2.3), at least until the mathematics is better demonstrated.

2.6.1 Wide Band and Active Cloaks

Expansion of the effective bandwidths is probably the most prominent issue for realizing a cloak like those used in *Star Trek*. Dr. David Smith at Duke is of the opinion that the problems of narrow bandwidth will be solved over the next half-century and some sort of wide band cloak will be available, either by mastering more parameters within the mathematics or by producing cloaks that use energy to produce canceling waves. Much research is being conducted on metasurfaces that can be tuned to different frequencies, based on the needs at the time. These frequency-selective metamaterials are active cloaks, energy is used to alter the

characteristics of the metascreen, giving it a different impedance, permittivity, or polarization (depending on the techniques used) and therefore changing the frequencies over which it is effective. This is in fact how the skin cloak of Ni et al. (2015) works. The gold nanoantennae are switched on with a small current that changes their polarization and makes them functional over the entire visible spectrum, a much broader bandwidth as compared to passive cloaks.

Dr. Alu is of the opinion that active cloaks are the only possible way to increase bandwidth significantly. He recently proposed an active cloak with a battery pack that would be effective over a very large range of radio frequencies (Chen et al. 2013). However, even with this advancement, Dr. Alu believes that cloaks in the visible range will not be realized anytime in the near future. Dr. Smith agrees, he doubts that a cloak that is effective against all EM frequencies will be possible for decades, and will likely require active technology. Perhaps Spock was right all along, cloaks might be possible, but they will be a terrific drain of energy. Then again, it may not be necessary to cloak over all wavelengths, planes don't need to be cloaked against visible light to avoid radar, and many fly too high to be spotted from the ground. Cloaking for specific frequencies may be sufficient.

2.6.2 *Slow Light and Positional Cloaks*

One of the most unbelievable things about transformation optics is its ability to slow down light. The speed of light is nearly constant; it travels only 0.03 % slower in air than it does a vacuum, although it slows by 3 % in glass—this is the basis for the index of refraction of a material. Yet there are ways to slow light down without moving it from one medium to another. Slow light could yield an amazing cloaking device; by the time the image of your ship arrives at that Borg vessel that is trying to assimilate you, you won't be there anymore. This is not unlike how light traveling extremely long distances gives a view of events in the past at that location. A transformation optics cloak might achieve the same thing by making the light take a bit longer to get to an observer.

One interesting way of slowing or even stopping light is by forcing a material that normally absorbs light to become transparent over a very small band of frequencies. This electromagnetic induced transparency (EIT) uses two lasers and takes advantage of the multiple quantum states allowed in a material's electrons (called superpositioning, Sect. 8.3.4). If a substance absorbs light over a certain range of wavelengths *and* a material's optical characteristics meet a set of very specific parameters, then a laser (the coupling laser) tuned to a near resonant frequency with one of the electron quantum states can make the material transparent to a very narrow range of frequencies within the absorbed range—a "spectral window" or "spectral hole." If a second laser (the probe) is shown on that material in the same area and is tuned to the frequency of the spectral window, it will be transmitted through the substance just like it was transparent, like looking through a brick wall (Fig. 2.8).

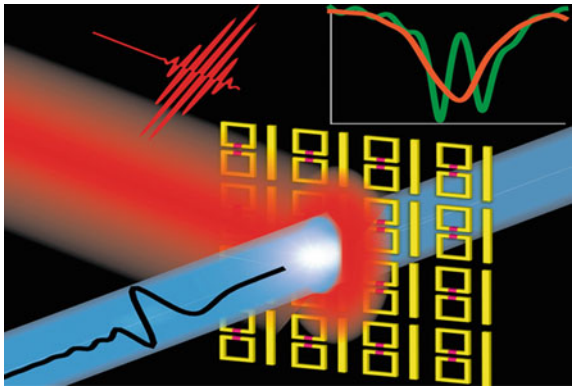


Fig. 2.8 Electromagnetic induced transparency uses two lasers. The *red* coupling laser, at one specific frequency is absorbed by the material (*yellow pattern*). The transmission spectrum at top right dips to zero showing it is not transmitted. The *blue colored* probe laser is a different set of frequencies; a few frequencies are transmitted through the opaque material as long as the coupling laser is on. This is indicated by the spike in transmittance in the *green line* in the graph at *top right*. If the coupling laser is shut off while the probe laser is on, the light will be trapped inside the opaque material until the coupling laser is turned on again. It can stop and start light. (*Image credit* Los Alamos National Laboratory)

This is interesting enough on its own, yet it gets weirder. When the coupling laser interacts with the material's quantum states, it very rapidly changes the index of refraction within that volume of material. An extremely fast change in refraction creates a large amount of dispersion of light, with parts of the ray passing through the material at each point along its change in refractive index so each is refracted to a different degree. A large range of refractions is called dispersion, like our example of the rainbow above where the different frequencies (colors) have different indices of refraction in water drops (see Fig. 2.2). When a narrow range of frequencies (the spectral window) undergoes extreme dispersion, the group velocity of the light slows down considerably, sometimes to just thousandths or millionths of the normal speed of light. Using techniques like this, light has been slowed down to just 17 m/s (38 mph) (Hau et al. 1999) and in other cases has been stopped completely using EIT in an ultracold cloud of strontium metal atoms (Ginsberg et al. 2007).

In a similar set of experiments carried out at the University of Darmstedt in Germany, scientists actually stopped the probe laser light in the substrate material. Since the coupling is what made the substance transparent to the probe laser frequency, turning the coupling laser off stopped the probe light inside the opaque solid. They had imprinted the probe laser signal with a picture of three horizontal bars, so in essence, this information was trapped in the solid as stopped light. A full minute later, the researchers turned the coupling laser back on and the probe laser light restarted and traveled through the rest of the material (Heinze et al. 2013). In its current state, this technology uses very small amounts of very cold gas molecules (called a Bose-Einstein condensate) and manipulates light over an extremely low

number of frequencies for fractions of a second and across distances of less than an inch. The mechanics of the system would ostensibly work over larger distances and wavelengths as well, although the number of materials with which to work is limited because the characteristics of the quantum states to produce a spectral window are very specific.

Since this mechanism of slow light production utilizes the dispersing properties of the material, it is called material dispersion, slightly different than waveguide dispersion techniques that use guided pathways for the waves as a means of inducing dispersion and slowing light. Metamaterials can be designed as waveguides that are specific geometric shapes and generate either negative permittivities and/or negative permeabilities that create group velocity changes and huge dispersive effects based on the wavelength of the light. These metamaterials have been used to slow down (Lu et al. 2009) or even stop light (Tsakmakidis et al. 2007) in transparent materials embedded with nanowires of copper. In a waveguide, the total dispersive effect is roughly an addition of the material dispersion and the waveguide dispersion, but some materials for optical communication devices can be produced where these two parameters cancel each other out and have zero dispersion.

Waveguide dispersion has also been achieved with a photonic crystal, which is basically several metamaterial layers put together to form a waveguide (Alagappan and Ping 2015) and also with micro-resonator metamaterials that act on light as if they were 10 cm (4 in.) thick even though they are flexible sheets only 1/1000th as thick (Hokmabadi et al. 2015). It is important to realize that all these metamaterial slow light generators are passive; it is the geometry of their constituents that produces the dispersion that slows light. This is direct contrast to the huge energy input needed to produce Bose-Einstein condensate material dispersion devices. However, waveguide dispersion generators also come with some of the limitations of metamaterial cloaks, including the difficulty in reducing unit cells to subwavelength sizes when moving from microwave or terahertz radiation up into infrared and visible light and the limited frequencies over which these cloaks are functional.

Luckily, even if the slowing of light to create a positional cloak proves difficult, the concept of slow light may help other cloaks work better. One problem with current metamaterial cloaks is that a moving cloak can't keep up with the changes to the background scenery and the light coming to the observer gets blurred. This has to do with the limited ability to speed up the phase velocity of all wavelengths when bending light around a cloaked object. By introducing a small optical device that the undergraduate developer at the University of St. Andrews calls an "invisible sphere" into a cloak, it can slow the light down in all frequencies (colors) so that the when the wave front is sped up again, the speed required does not surpass the limits of the material (Perczel et al. 2011). Therefore, all the colors of the wave front travel together and the observer sees a crisp image even if it is changing rapidly.

2.7 Conclusion

Disguises, camouflage, stealth technology—mankind often goes out of his way not to be seen. Whole technologies and commercial markets are based on the sole idea of keeping things hidden. While cloaking is the next step in this line, there are differences between cloaking and the other methods of hiding that make it both better at its job and harder to accomplish. It is clear that cloaking is more than just camouflaging or disguising an object to look like something else. The point is not to have the object just blend into the background, but to be undetectable while preserving the environmental signals that would normally be hidden by the object's presence. More than stealth, cloaking doesn't just prevent a signal from being detected, it allows for the detection of normal signals, the situation to be expected if the object wasn't there at all.

Camouflage is often limited by positional issues. The camouflaged object blends in from one direction, yet the same camouflaged object may stick out like a sore thumb from another direction. Birds and fish are colored differently on their backs and bellies just to avoid this problem. This makes them less visible from below and above, although changes in the background may still point them out to their predators. True cloaking renders an object invisible from all directions at all times, no matter the movement of the object, the observer, or the background. Unfortunately, this strength of cloaking is also one of the reasons it is so difficult to achieve. Current cloaking methods are limited in frequency range, size, dimensions in which they are functional, and mobility. Metamaterials have opened up the field of cloaking, but the transformation optics discipline is so young that most cloaks are only functional over very narrow frequency ranges. As of now, the expansion of bandwidth destroys very optical characteristics that render an object cloaked. Likewise, expanding the number of dimensions (X, Y, Z) in which the cloak is active makes the mathematics and production of the metamaterial much more difficult. Only a few current metamaterial cloaks are attachable to the object being cloaked, so for the majority, the cloak is immovable and the object must remain unmoving as well.

While these limitations are real and difficult to overcome, one must realize that the progress that has been made in just the past two years has been amazing. The expansion of cloaking types from gradient index to the thinner mantle cloaks has made cloaking moving objects easier, although the need to take the target object's optical characteristics into consideration introduces another issue that must be dealt with. Likewise, the advent of slow light technology portends the development of positional cloaks, yet have limitations of their own. As of now, positional cloaks use ultracold atoms, the choice of atoms is limited, and the distances over which light can be slowed are much too small to be useful in making a starship disappear.

Overall, the take home message is that cloaking is very real, very young, and very misunderstood. Most of the people who work in these fields cringe at the mention of *Star Trek* or Harry Potter cloaks. The possible applications for cloaking beyond movie tricks and military tactics are numerous and important. The same technology

that *could* hide a starship from detection *will* improve wireless communication, open up the field of optical computing, and improve information security through communication devices. Space exploration will be aided by metamaterial thermoelectric and heat dissipation technologies as well as cheaper and lighter communication instruments that are based on the materials being developed now. Medical imaging, landmine detection, cheap and less intrusive airport scanners, even allowing a surgeon to see around his hands to get a batter view of field—the uses of cloaking technologies are limited only by the imagination of the engineers. Even if Gene Roddenberry refused to let his heroes hide, perhaps he could see that humanity may be able to use cloaking technology and still hold on to their moral center.

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