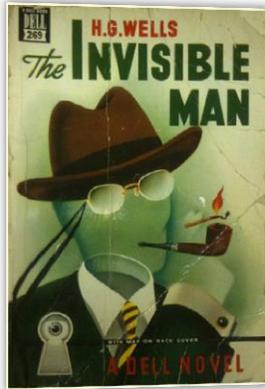


On the Quest to Invisibility: *Meta*-materials and Cloaking

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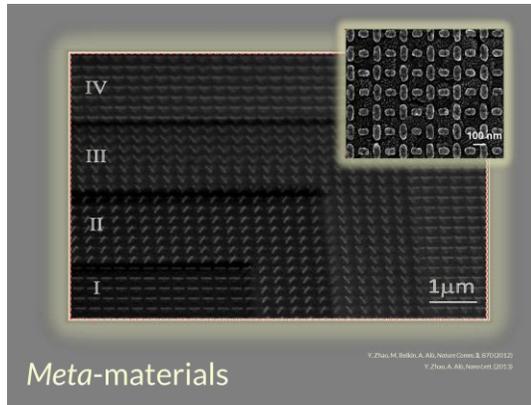
In his 1881 novella “The Invisible Man”, H. G. Wells describes a scientist who devoted all his life to research in optics and eventually comes up with a practical way to make bodies invisible to the human eye. Wells was not the first writer to talk about invisibility but with his fervent imagination and clear descriptions of the involved optical processes he has fascinated generations of readers, movie directors, and even many scientists... There is also that little bit of voyeurism in all of us that gets excited at the idea of hiding behind an invisibility cloak and observing what happens around us without being seen.

Human fascination for controlling and manipulating light is definitely older than Wells, it is probably safe to say that it is as old as mankind. What you see in this picture is the Lycurgus cup, a Roman glass vase realized over 1500 years before Wells. It is currently housed at the British Museum in London and has a unique optical property. If you look at the cup when illuminated from the back, the object is red, but when is illuminated from the front with light passing through it, it actually looks green. Ancient Greeks and Romans had learned over centuries of experiments, trial and error that by carefully melting tiny amounts of precious metals into glass they could obtain such a surprising optical effect. If you looked at the vase under a microscope, you would be able to see, dispersed here and there, tiny silver and gold alloys. The average size of these metallic nanoparticles is about 70 nanometers, 10 thousand times smaller than a single grain of sand. After centuries of study, we now know that the specific material proportions, the size of these nanoparticles and the density with which they are embedded into glass form the exact combination that can unlock this unique optical effect. It is quite amazing to think how these artists a couple of millennia ago were able to realize these material tricks with simple tools and a lot of ingenuity.



The Lycurgus Cup, 300AD, British Museum, London, UK

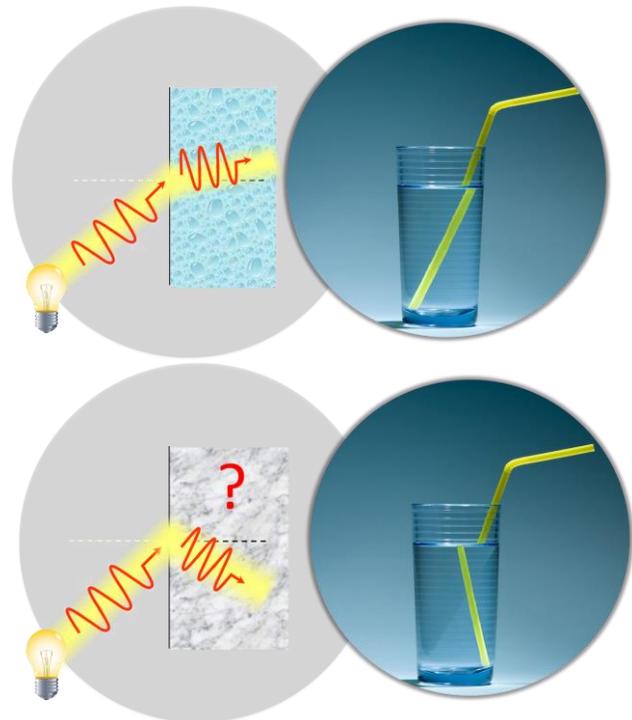
Now let's travel a few centuries later to Northern Europe. By that time, these same techniques had been further mastered to realize the uniquely bright colors that we can admire in stained glasses decorating thousands of churches. Also at these times, the artists working on these masterpieces did not know all the laws of optics that govern these phenomena, but with hard work and amazing skills they were able to develop the precise combination of metallic nanoparticles required to turn an ordinary glass into a marvelous piece of art. What those artists did not imagine is that they would become the precursors of the modern scientists that today are unveiling the mysteries of light interacting with matter, and that these stained glasses, as I will show you in a moment, are the ancestors of the modern technology that may be able to realize Wells' dream of an invisibility cloak.



Today, we are in a particularly exciting period in history, because with modern nanotechnology tools we can control with extreme precision the shape, size, orientation, composition, alignment and density of these nanoparticles to realize optical effects that were believed impossible even only a few years ago. To give you an idea of the modern 'stained glasses' that we are now able to produce, these are a couple of microscope images of artificial materials recently produced in my lab. What you see here are extremely thin layers of glass stacked on top of each other and adorned with perfectly aligned tiny

gold nanorods, even smaller than those found in the Lycurgus cup. You may argue that these are not as nice looking as the stained glasses we saw a minute ago, but I can assure you that they have far more reaching implications in the future of optical devices and camera sensors. In the past ten years we have seen an unprecedented growth in the realization and physical understanding of these nanomaterials. We have come to realize that by controlling the material composition at the nanoscale, it may be possible to challenge rules and limitations that were for centuries considered written in stone. This is essentially how a new field of science and technology has started, the field of *meta*-materials. By their same definition, metamaterials are man-made materials with properties that transcend the ones of natural materials.

As an example of how light can be tricked by metamaterials to do things we would not expect, consider one of the most common optical phenomena, the *refraction* of light at an interface between two materials. Refraction simply means that when an optical beam enters a material, say water, from air, it changes the direction in which it travels. This is actually the combined effect of billions of water molecules interacting with the incoming light, which, as a result, gets bent. The denser the material, the more bending we see. This phenomenon actually explains why a straw in a glass of water looks broken. In 1968 a young Russian physicist published his first scientific paper on a simple, but rather obscure theoretical question: what if we were able to find a material with a *negative* index of refraction? The refractive index is exactly what I just described, it tells us how much light is bent when it enters a new material. It is '1' for air, and it is larger than 1 for practically any other material. Victor Veselago, this was the name of the scientist, asked himself what optical effect he would



Positive (top) vs. negative (bottom) refraction

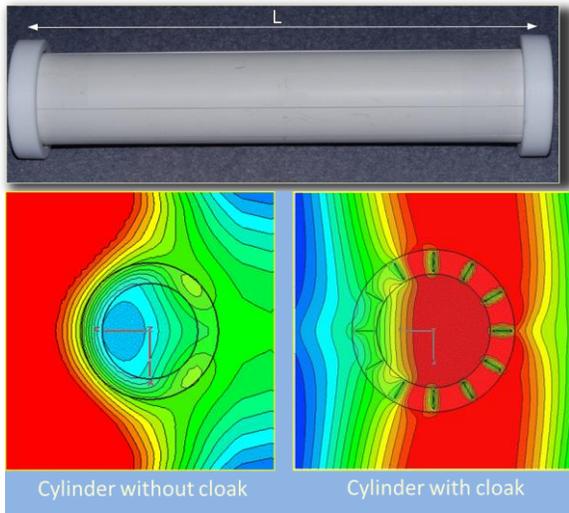
get if this quantity got hypothetically negative. This is what he predicted: light would bend the 'wrong' way. If we could find a negative-index material in liquid form, this is what our straw would look like.

Veselago's paper didn't receive much attention at the time of publication, nor in the following years... That's not too surprising: it was hard to believe such materials could exist and, even if they did, we wouldn't know what to do with them. Still, he spent the rest of his career looking for one, and his quest eventually ended 35 years later when a group of scientists at UC San Diego was able to experimentally create the first example of a *negative-index* metamaterial. 35 years, this is how long it can take for a challenging idea to go from dream to reality... Like the images I showed you earlier, the composition, shape and arrangement of specifically designed 'artificial molecules' provided a new recipe to produce an effect that was considered impossible. What scientists had come to understand during these 35 years was that, like water molecules bend light in the 'usual' way, properly designed *metamolecules* can bend light in the opposite way.

This is how our journey to invisibility has essentially started. With a few colleagues we realized that if we can trick light to go in the wrong direction using metamaterials, we could think of even more exotic effects!... Invisibility and cloaking represent today the most exciting phenomena so far achieved with metamaterials. The possibility of realizing this effect has spurred the imagination of scientists and lay people, connecting metamaterials with something that we had so far only dreamed in novels and movies. In the last eight years, several proposals have been made to apply metamaterials to invisibility. How would it work? Well, when a beam of light hits an object, it is reflected and scattered around by its surface. This is essentially how we see the object, by collecting a portion of these scattered waves. If we were able to avoid the interaction between light and the object and eliminate these scattered waves, then the incoming beam would essentially go undisturbed through the object, making it invisible to anyone around it. Notice that the challenge here is not only to eliminate reflections, this is what stealth technology already does on military planes. What we want to achieve is much more challenging, suppress any interaction between the object and light to eliminate even the shadow and making it completely undetectable.

One idea is to use metamaterials to carefully 'bend' light rays right around an object, like a form of mirage. My colleagues and I have worked on a different approach and proved in 2005 that properly designed metamaterials can be made to scatter a form of 'negative' light. If we manage to balance the positive scattering from the object and the negative scattering from the metamaterial, the overall effect would be to cancel the scattered wave and produce an invisible object. The wave would just go through without scattering, and you would not even see its shadow. After we proposed the idea and started working on an experiment, we discovered that Wells had already figured it all out. In his novella he essentially describes the same idea in lay terms: Griffin, the crazy scientist, based his discovery on a method to change a body's refractive index to the one of air, so that it scatters no light. Putting it in Wells' own words, Griffin devised *'a method by which it would be possible, without changing any other property of matter to lower the refractive index of a substance so far as all practical purposes are concerned. Either a body absorbs light, or it reflects or refracts it, or does all these things. If it neither reflects nor refracts nor absorbs light, it cannot of itself be visible'*. When I first read this, I found quite

amazing that a writer from the 19th century was able to imagine these difficult concepts and describe them in such simple yet powerful words?



Last year our group at the University of Texas at Austin was able to show for the first time invisibility of a three-dimensional object. Instead of targeting the visible spectrum, we worked with radio-waves. They are governed by the same physical laws as light, but they make the experiment easier because they are longer. We took a cylinder, over half-foot long, and covered it with a metamaterial cloak that was carefully designed to have an electromagnetic response that is the exact *opposite* of the one of cylinder. We achieved this effect by inserting carefully designed metallic plates in a ceramic material, a little bit like the stained glasses I showed you a few minutes

ago. Our measurements proved that total transparency of an object is possible, for different angles and observer's positions, even very close, or right behind the object. To understand better what this looks like, in this animation you see a radio-wave hitting the original cylinder from left to right. As you see, the wave is strongly distorted and perturbed by the presence of the cylinder. It looks like it is bouncing off its surface. This interaction is essentially what makes us see the object. Once we add our cloak, the wave goes through it as if the object is not there, and the cylinder becomes invisible to radio waves! I can tell you that this is essentially what we were able to measure in our laboratory. If you were to sit right behind the cloaked cylinder you would see the wave coming through it towards you, without being able to notice that there is an obstacle in between. For all practical purposes the cloaked cylinder has no

shadow and is invisible to radars! Not quite human eyes yet, but the concept is essentially the same.



Potential applications: non-invasive probing, green-energy, optical nanodevices

We are now working to apply this technology to larger and more complicated shapes; to collections of objects, and to different frequencies. We are not only thinking to the obvious applications, like defense and camouflaging, but also to a variety of other fields of practical interest. Imagine if we could make *invisible antennas* that can receive signals without being detected. Isn't this the modern way of hiding behind an invisibility cloak and seeing without being seen? These invisible antennas would also not interfere with each other on a crowded roof or a tower station. We can apply a similar idea to

near-field microscopes, drastically improving bio-medical sensors and measurements. We are also thinking of ways to apply this technology to improve the efficiency of light absorption for green-energy

applications, to make optical nanotags for unique biological identification, and to conceive optical nanodevices for the next generation of ultrafast, optical computers.



If you don't care of these technological advances, and are just dreaming of getting a cloak of invisibility sooner rather than later, I have to warn you that Wells' story doesn't end so well: Griffin successfully carries out the experiment on himself, but he fails at his attempt to reverse the procedure and stays invisible forever. He gets betrayed by his best friend that doesn't keep his secret. So Griffin murders him and begins a 'reign of terror'. I am confident that the future of metamaterials is much brighter than Griffin's story. I like to think that

our metamaterials are the new stained glasses of the 21st century –just a bit less colorful than the old ones. In our ongoing fascination and pursuit to change the way light interacts with materials, we are getting closer to bringing fiction to reality and we have shown that, by thinking out of the box, it is possible to overcome established limitations of science and technology. At the end of the day, this is only a 10 year-old field of study....