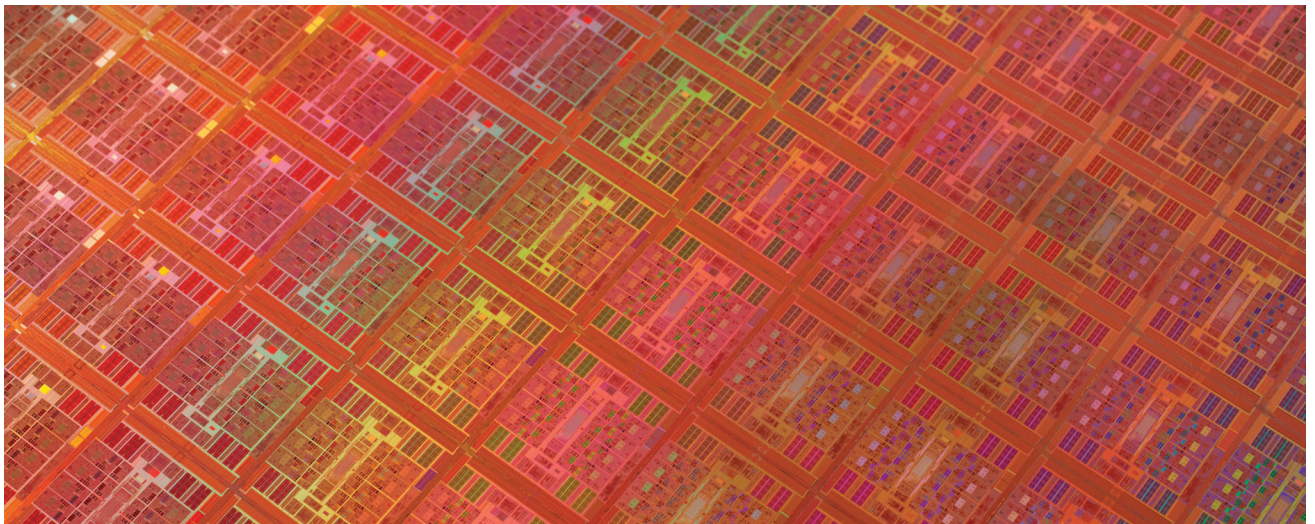


A 100-FOLD IMPROVEMENT IN LITHOGRAPHY RESOLUTION REALIZED WITH A 150-YEAR-OLD “PERFECT IMAGING” SYSTEM

Madrid researchers have used computer modeling to demonstrate that Maxwell’s long-theorized fish-eye lens is not just a theory. It could be the way to transform the lithography and microscopy industries and, by extension, electronics

By **DEXTER JOHNSON**



BACK IN THE mid-19th century, the famed Scottish physicist James Clerk Maxwell proposed a “perfect imaging” system with a positive refractive index. The gradient index lens he proposed—dubbed the Maxwell fish-eye (MFE)—is a lens that can image any point outside the lens to a corresponding point on the same surface. It was supposedly capable of “perfect imaging,” in which the smallest details could be resolved to unlimited sharpness.

Over the next 150 years, Maxwell’s “perfect imaging” proposal was considered impossible to realize since light diffracts around any point that is the same size or smaller than its wavelength—the so-called diffraction limit. This diffraction limit made it impossible for any lens to resolve a detail smaller than that particular wavelength of light.

But starting in 2000, research in a new field of opti-

Magnified view of a semiconductor wafer patterned via photolithography—a technique that may benefit from new high resolution imaging methods.

IMAGE: STEPHAN HOEROLD/
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cal materials—dubbed metamaterials—began to suggest that perfect imaging could be achieved through something called negative refraction, in which light bends in the opposite direction from that of typical refraction. And in 2004, researchers proved that a negative-refraction material could be made that would focus radio waves below their diffraction limit.

In 2009, however, Ulf Leonhardt, then of the University of St Andrews in Fife, Scotland, offered another approach to obtaining perfect imaging. His idea did not require the

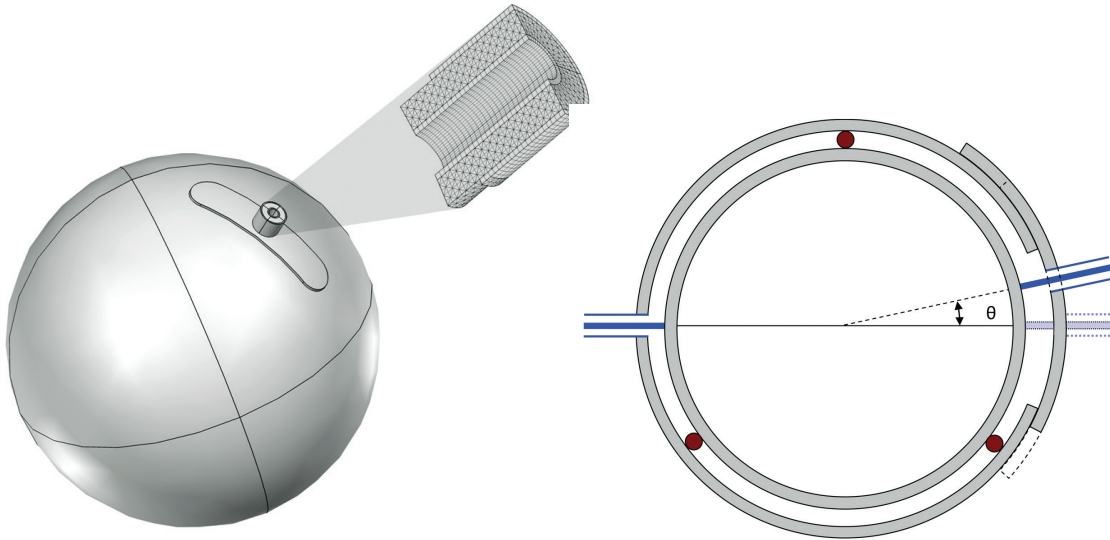


FIGURE 1: SGW with the drain port on top (left), where a cross section of the coaxial cable and its mesh are shown together with a schematic representation of the SGW cross section (right).

negative refraction of metamaterials. He proposed that perfect imaging could be achieved with ordinary positive refraction materials. In offering his proposal, Leonhardt theoretically analyzed the MFE and demonstrated that its focus is not restricted by the diffraction limit.

If Leonhardt's theory was possible, then key optical industries such as lithography and optical microscopy could be revolutionized. Perhaps more important, it might let the chip industry create chip features smaller than had ever been thought possible.

"Clever ways around the resolution limit of imaging may be truly revolutionary for photolithography, the key technology of the microelectronics industry," explains Leonhardt, now a researcher at the Weizmann Institute of Science in Israel. "Instead of investing billions in making conventional imaging systems work with light of increasingly short wavelengths, unconventional imaging may do the trick with conventional light."

A research team at the Cedint Polytechnic University of Madrid in Spain, led by professor Juan Carlos

Miñano, was intrigued by Leonhardt's theory. The team followed up on his line of work and demonstrated through simulation that diffraction limits can be surpassed in the MFE.

In order to prove the theory, they proposed a device that has equivalent optical properties to an MFE and that they called a spherical geodesic waveguide (SGW). An SGW is a very thin, spherical metallic waveguide filled with a non-magnetic material (see Figure 1).

While it was a breakthrough to demonstrate that perfect imaging with a positive refractive material was possible, today just about

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everything related to SGWs—and by extension MFEs—is still theoretical.

Currently, some of those same researchers at the Polytechnic University of Madrid who first proposed the SGW are again turning to computer modeling and simulation technologies to determine the manufacturability of such a device so a prototype can be fabricated and tested. If the team can figure out a way to produce these devices in simulations, the ability to apply them to lithography and optical microscopes will move from being merely a theory to a reality.

Dejan Grabovičkić from Polytechnic University of Madrid and one of the researchers on this project, notes that the simulations they have done with COMSOL Multiphysics and the RF Module have resulted in models that demonstrate that SGWs can be manufactured for certain applications.

"In general, [an SGW] is applicable in optical systems where the object and image planes are connected with the optical system, for example in microscopy and lithography," explains Grabovičkić. "In

the case of lithography, the size of the electrical components directly depends on the laser wavelength, which is now about 200 nanometers. Perfect imaging could reduce this size and permit us to build the integrated electronics in very small dimensions, much smaller than what is the state of the art—something like 100 times smaller.”

To better understand how an SGW is capable of having such a dramatic effect on both lithography and microscopy, one first needs to understand how a waveguide operates. A waveguide is a physical structure capable of transmitting electromagnetic signals. As opposed to transmitting electromagnetic signals through the air, with a waveguide electromagnetic energy is confined between the guide’s walls.

While conventional waveguides have linear symmetry and are used for signal transmission over large distances, SGWs have spherical symmetry and are more useful for short-distance transmissions. Other than that, the physical principles are the same.

The critical capability the SGW possesses to overcome the diffraction limit is something called super resolution, which is the ability of a system to sense a small change in the position of the receiver that is much less than the electromagnetic radiation wavelength. When Miñano’s team first proposed the SGW, two coaxial cables were used, acting as a small source and receiver (see Figure 1). A change in the position of the receiver smaller than the wavelength of the electromagnetic wave caused a significant drop in transmitted power (see Figure 2). That meant that the system possessed super-resolution and opened a space for further research into possible applications of the device, especially its use in perfect imaging.

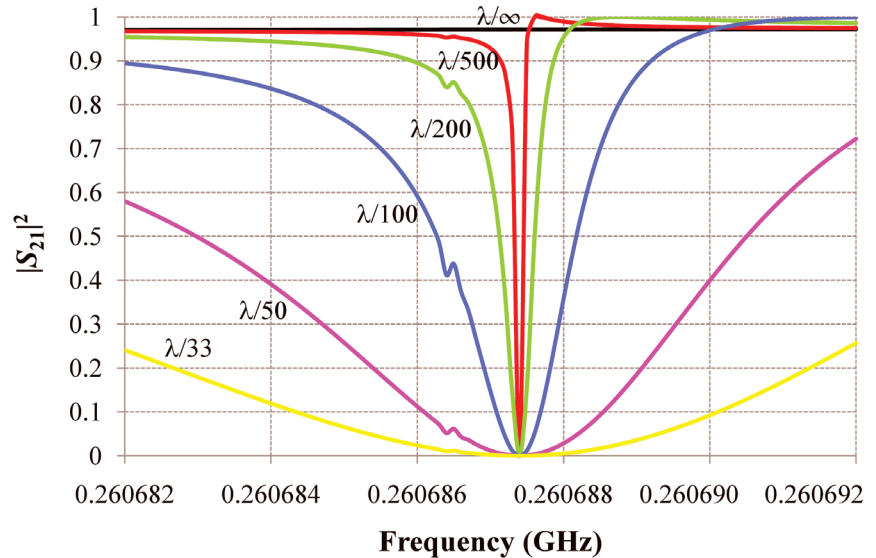


FIGURE 2: Results of the transmitted power in the SGW as function of the frequency for different drain port positions (the corresponding shift, expressed as a fraction of the wavelength, on the inner sphere of the SGW between the drain port center and the source port antinode has been used for labeling). A strong drop in the power for a small displacement of the drain port indicates super-resolution property of the SGW.

COURTESY OF DEJAN GRABOVIČKIĆ AND JUAN CARLOS GONZALEZ

Now Grabovičić and his colleagues have shown through computer modeling that just such an SGW device can be built. But in order to create this model, the Madrid researchers couldn’t use geometric optics, in which electromagnetic waves are repre-

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OF MADRID

sented by straight lines and follow well-defined rules. Instead, they had to depend on wave optics.

“In some cases, the propagation of the electromagnetic waves can be calculated analytically, but in general we should use simulation,” explains Grabovičić. “COMSOL Multiphysics included tools for electromagnetic analysis that we needed for this modeling. The very complex equations that are necessary for 3-D super resolution and super imaging systems can be solved successfully in this software using sophisticated numerical algorithms.”

The SGW that the researchers have realized through COMSOL Multiphysics works for microwaves. The next step in the research, which the team has already started to work on, is to design a dielectric SGW that will work in the visible spectrum. ©