Study shows way to design 'digital' metamaterials

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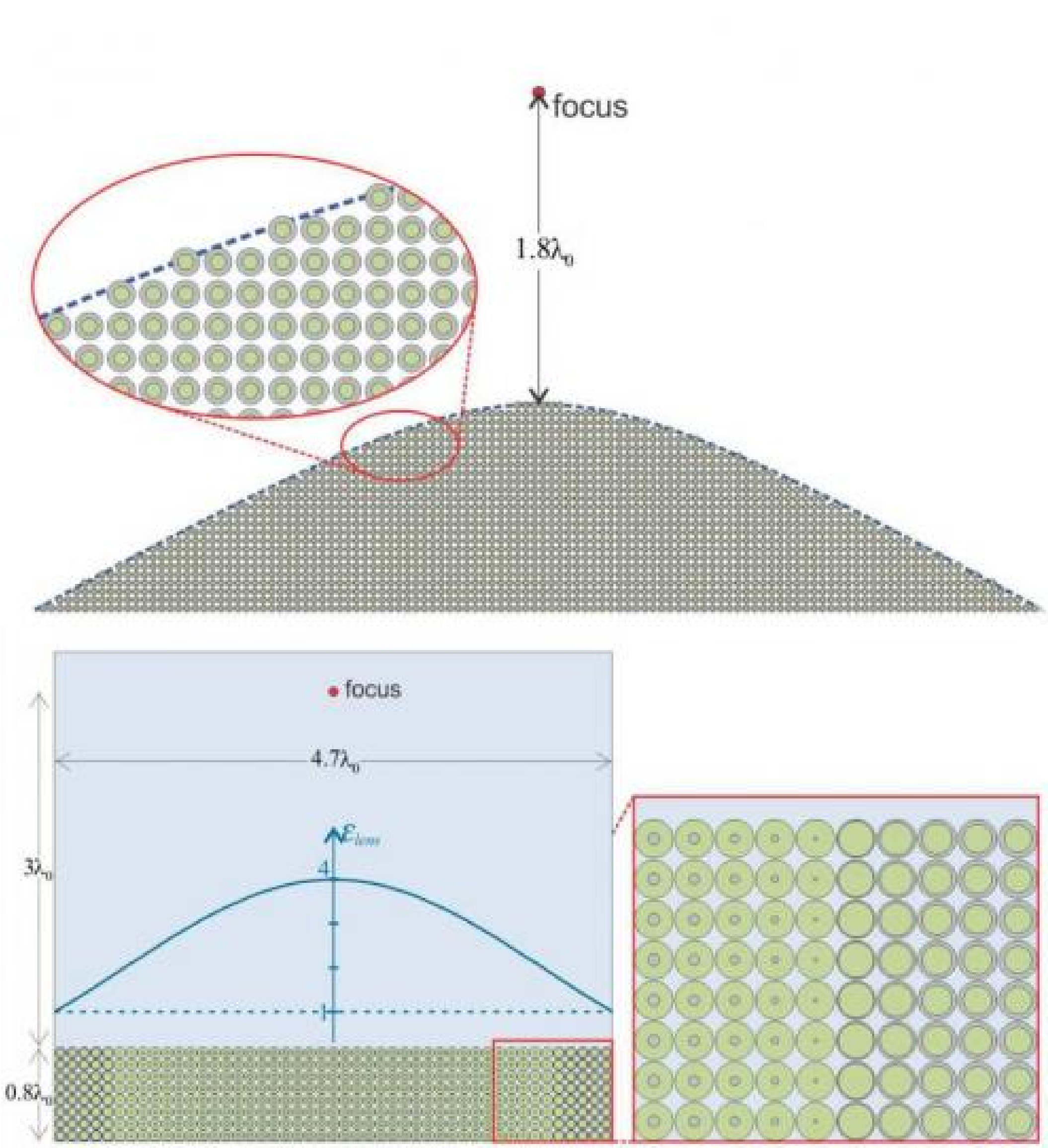


A metamaterial with a given permittivity can be designed out of any two materials, called 'metamaterial bits,' so long as the permittivity of one of the materials is positive and the other is negative. Borrowing terms from binary computing, these 'digital' metamaterials are composed of metamaterial 'bits,' which are combined into 'bytes.' A lens made out of identical metamaterial bytes (above) can be made flat by altering the composition of the bytes (below). Credit: University of Pennsylvania

Metamaterials, precisely designed composite materials that have properties not found in natural ones, could be used to make light-bending invisibility cloaks, flat lenses and other otherwise impossible devices.

Figuring out the necessary composition and internal structure to create these unusual effects is a challenge but new research from the University of Pennsylvania presents a way of simplifying things. It shows that a metamaterial with a given permittivity can be designed out of any two materials, called "metamaterial bits," so long as the permittivity of one of the materials is positive and the other is negative.

Borrowing terms from binary computing, these "digital" metamaterials are composed of metamaterial "bits," which are combined into "bytes." These bytes can take different shapes, such as nanoscale cylinders consisting of one of the metamaterial bits wrapped in a shell of the other. In the case of the cylinders, by altering the radii of the cores and shells, as well as which of the two bits is on the inside or outside, the researchers were able to mathematically demonstrate that a bulk metamaterial of nearly any permittivity is achievable.

Furthermore, they have shown that by carefully arranging these bytes into more complicated overarching patterns, flat lenses, hyperlenses, and waveguides can be produced.

The study was conducted by Nader Engheta, the H. Nedwill Ramsey professor of Electrical and Systems Engineering in Penn's School of Engineering and Applied Science, and Cristian Della Giovampaola, a postdoctoral researcher in his research group.

The study is featured on the cover of the December issue of *Nature Materials*.

"The inspiration came from digital electronics," Engheta said. "With binary systems, we can take an analog signal—a wave—and sample it, discretize it and ultimately express it as a sequence of 0's and 1's. We wanted to see if we could break down a material's electromagnetic properties in the same way.

"When you digitize a signal, you look at its magnitude in each point in time and give it value. We're applying the same process to materials, looking at the permittivity it would need to have in each point in space in order for it to perform the function we want."

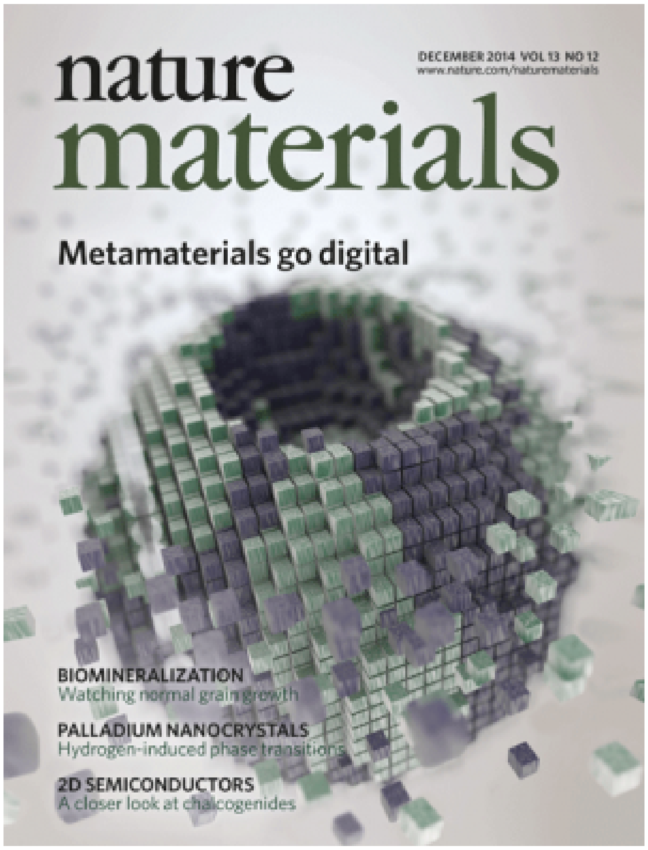
Permittivity is the property of a material that describes its reaction to an electric field inside it. As such, it's a key quality to consider when designing optical devices, such as lenses and waveguides. Materials with the desired permittivity may not always exist in nature, however.

"We can't just combine two materials and get the average of their permittivity values," Engheta said. "You might not even get a value that is between the two; combining a material with a permittivity of 2 and one of -4 might give you a material with a permittivity of 30. The geometry of how they are arranged with respect to one another is very important to getting to the value you want."

This phenomenon is critical to the design principles behind digital metamaterials bytes. For a certain set of metamaterial bits, when the material with positive permittivity (typically a dielectric) is on the inside, the permittivity of the byte ranges between the values of two the materials. When the material with negative permittivity (typically a metal) is on the inside, however, the overall value varies widely outside that range. Fine-tuning the ultimate permittivity of a byte then entails altering the thickness of each of the materials.

For simplicity's sake, the researchers simulated metamaterial bytes made out of silver and glass in their study, but stressed that any pair of materials that followed the negative/positive rule would work.

"If I want a metamaterial with permittivity of 14, I can pick any two materials, as long as one is positive and one is negative, and select them based on the other properties I need for my application," Engheta said. "Silver and glass, for example, might not have the right mechanical or thermal properties for what I want to do, so I can select other materials and get to the permittivity I need by altering the radii and order of them in the metamaterial byte."



Ella Marushchenko and Alex Tokarev. Cover Design: David Shand.

"This gives us a lot of flexibility," he said. "It's just like how I can select the voltage I want to represent a '1' in an electronic circuit. If it's a regular circuit in the lab, a '1' might be 5 volts, but if it's a nanoscale device, I might want to have a '1' be 5 microvolts."

The researchers selected the core-shell geometry of the bytes because it is a structure that materials scientists are already adept at constructing. Alternate byte geometries, such as ones constructed out of alternating layers of the two materials, are possible.

Once bytes are constructed, the way they are arranged in proximity to each other enables various optical applications.

"If we wanted to make a lens with a permittivity of 4, but didn't have a single material with that value, we could take any two materials with the positive/negative rule and design bytes such that they each have a permittivity of 4," Engheta said. "If we arrange them together in the shape of the lens, the whole thing looks like it has a permittivity of 4 from the perspective of a light wave, even though none of the materials in it have that value."

"We can take it a step farther, and make a flat lens that focuses light in the same way," he said. "We could arrange bytes in a layers, but instead of their height changing, we change their permittivity so that it bends the wave in a manner expected from the lens."

With the ability to spatially vary the permittivity of a metamaterial in such a discrete way, other optical applications are just a matter of the proper arrangement. The researchers demonstrated the feasibility of digital metamaterial hyperlenses, which can image things smaller than the wavelength of light, as well as waveguides that channel light around curves and corners. Carefully arranged such that they channel light around an object, such waveguides would create the illusion of light passing through the object unimpeded, effectively rendering it invisible.

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Provided by University of Pennsylvania

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