Viewpoint

Photonic Crystals "Go Hyper"

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A design for a photonic crystal made with so-called hyperbolic metamaterials could provide unprecedented control of light waves confined to the surface.

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A Viewpoint on:
Photonic Hypercrystals
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Physicists continually strive to break boundaries in light control. Recent device conceptions, such as invisibility cloaks, slow light waveguides, and all-optical circuits, tame light and mold its path in ways unimaginable some decades ago. A potential new frontier where two types of photonic media—one-dimensional photonic crystals and hyperbolic metamaterials—are combined into something called a "photonics hypercrystal" [1] has now been proposed by Evgeni Narimanov from Purdue University, Indiana. In theoretical calculations, he has demonstrated that light waves confined to the surface of a photonic hypercrystal would borrow individual merits from photonic-crystal-like and metamaterial-like surface waves. These results open a new regime of metastructure designs where light waves are controlled synergistically on two entirely different length scales.

Two technologies that have greatly contributed to our ability to control light are photonic crystals and metamaterials. Typically, these two types of photonic media are considered mutually exclusive. Photonic crystals (PCs) are mesoscale systems comprised of periodically arranged material building blocks, whose typical spacings are about half the wavelength of the impinging light wave. Examples include diffraction gratings, optical coatings, and even butterfly wings. The key light control in these structures arises from a combined effect of multiple scattering between, and light resonances within, the material elements [2]. A judicious choice of the constituent materials and building block arrangement may lead to a plethora of phenomena including complete reflection, guiding, and confinement of light, as well as negative refractionlike behavior, which can be further exploited for super-resolution beyond the diffraction limit [3]. Metamaterials, on the other hand, have tiny elements—like metal wires and resonators—that behave like engineered atoms with exotic light responses based on their geometry. These elements are designed to be much smaller than the operating wavelength [4], so incoming light "sees" them as part of a homogeneous medium—like a regular solid, though with optical properties not found in nature. Researchers have used metamaterials to bend light in unconventional ways, offering the possibility of novel devices like perfect lenses, invisibility cloaks, or perfect absorbers [4].

In his new work, Narimanov considered a particular type of metamaterial called "hyperbolic," whose engineered components are extremely subwavelength, by an order of magnitude or more [5]. Characteristic structures have the geometry of stacked layers and include a material of metallic character, i.e., a material with a negative permittivity. Since these layers are so tiny, light sees each two-layer combination as a whole, or "meta-atom," with an averaged electric field. Now, depending on which direction light comes from, the electromagnetic boundary conditions determine a different average for the electric field and electric displacement [6]. As a result, the effective electric response of these meta-atoms is highly anisotropic, with the electric permittivity positive in one direction but negative in a perpendicular direction. This anisotropy can be controlled by the choice of materials that comprise the two-layer meta-atom as well as their volumetric ratio.

Because of this anisotropy, hyperbolic metamaterials have a very unique dispersion relation between the frequency and wave vector (momentum) of internally propagating light waves. In a regular refractive material like glass, the light modes for a given frequency all lie on a sphere in wave-vector space. But as a result of the directional sign change in permittivity, the light modes within a hyperbolic metamaterial trace out a surface defined by a hyperbola, hence their name [5]. Initially, this hyperbolic dispersion was thought to be exclusive to man-made structures (alternating layers of dielectrics with doped semiconductors, metals or polar materials),

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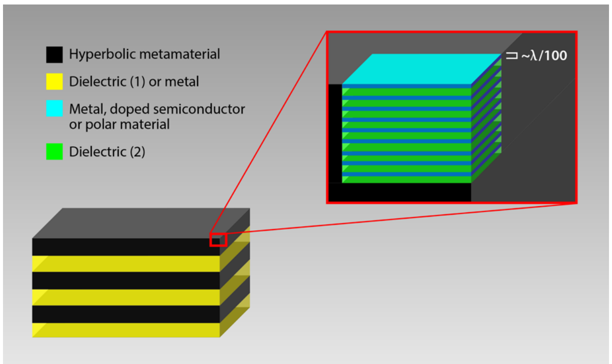

FIG. 1: The "photonic hypercrystal" is a photonic crystal made of a hyperbolic metamaterial. The structuring within the hyperbolic metamaterial has features about a hundred times smaller than the incident light's wavelength and twenty times smaller than the hypercrystal periodicity. The hypercrystal metamaterial blocks have ultrafine structuring (inset), which allows them to behave as uniform hyperbolic media even under near-field illumination. (APS/Alan Stonebraker)

but nowadays we know that it may also be found in certain natural materials (like sapphire, graphite, quartz) with a strong crystallographic anisotropy in their resonant phonon response to light waves.

Narimanov has opened potentially new applications for hyperbolic metamaterials by theoretically investigating their use as building blocks in a photonic crystal. In particular, he looked at a planar arrangement in which layers of a hyperbolic medium are interspersed with either a dielectric or metallic material. He considered both natural and man-made hyperbolic media. In the latter case, the hypercrystal structure is made up of multiple layers spaced at two different length scales—one very fine, at one-hundredth the operating wavelength and the other one coarser, at one-fifth the operating wavelength (see Fig.1). Narimanov calculated the dispersion relation for different cases of photonic hypercrystals and explored how light may propagate along their surfaces.

His findings suggest that hypercrystals enable a vast "playground" to engineer surface waves. These waves can typically be excited by the near field, which is the light that evanescently decays (rather than propagating away) from a source or scattering object. Surface light waves have a high intensity and are tightly confined at the material surface [7], making them attractive for sensing applications that require enhanced electromagnetic energy. In this regard, new materials that can support intense surface waves would be useful, particularly in the mid-IR—the spectrum that contains the characteristic frequencies of many biologically and chemically interesting molecules. Metal surfaces are typically not very good at localizing light in the mid-IR [7]. And while hyperbolic metamaterials on their own offer the potential of limitless degree of confinement, they must be oriented so that the negative permittivity is along the interface [8]. This poses some limitation in design flexibility and operational bandwidth for applications.

This flexibility should be available with hypercyrstals, which, unlike hyperbolic metamaterials, enable surface waves for both orientations of the hyperbolic medium's anisotropy with respect to the incident light. Surface waves are excited within the hyperbolic material component of the hypercrystal medium, when the negative permittivity is along the surface. Conversely, guided waves, like the waves within an optical fiber, are excited when the negative permittivity is perpendicular to the surface [8]. Either guided or surface waves within the hyperbolic medium interact via light tunneling, causing fields to be confined at the hypercrystal surface, while decaying away from it.

Photonic crystals and hyperbolic metamaterials have different strengths when it comes to supporting surface waves, and these attributes are combined in the photonic hypercrystal. For example, the hypercrystal medium supports several surface modes just like 1D photonic crystals do [9], which allows them to operate within a broader wavelength spectrum, even if the constituent hyperbolic material doesn't. On the flip side, there is no cutoff for the phase front density of the surface waves as there usually is in 1D photonic crystals. This is important because both the intensity and confinement of light waves are stronger for surface modes with denser phase fronts. Most importantly, the structuring of hypercrystals provides an avenue to mitigate the losses typically present in surface modes in metals and metamaterials. This is true even for surface wave excitations of very high phase front densities, as Narimanov has demonstrated [1].

Hypercrystal photonic media hold great promise as platforms for sensing with mid-IR light. Even beyond surface waves, the photonic hypercrystals could open a new research domain for wave control by material structuring on separate lengths scales.

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