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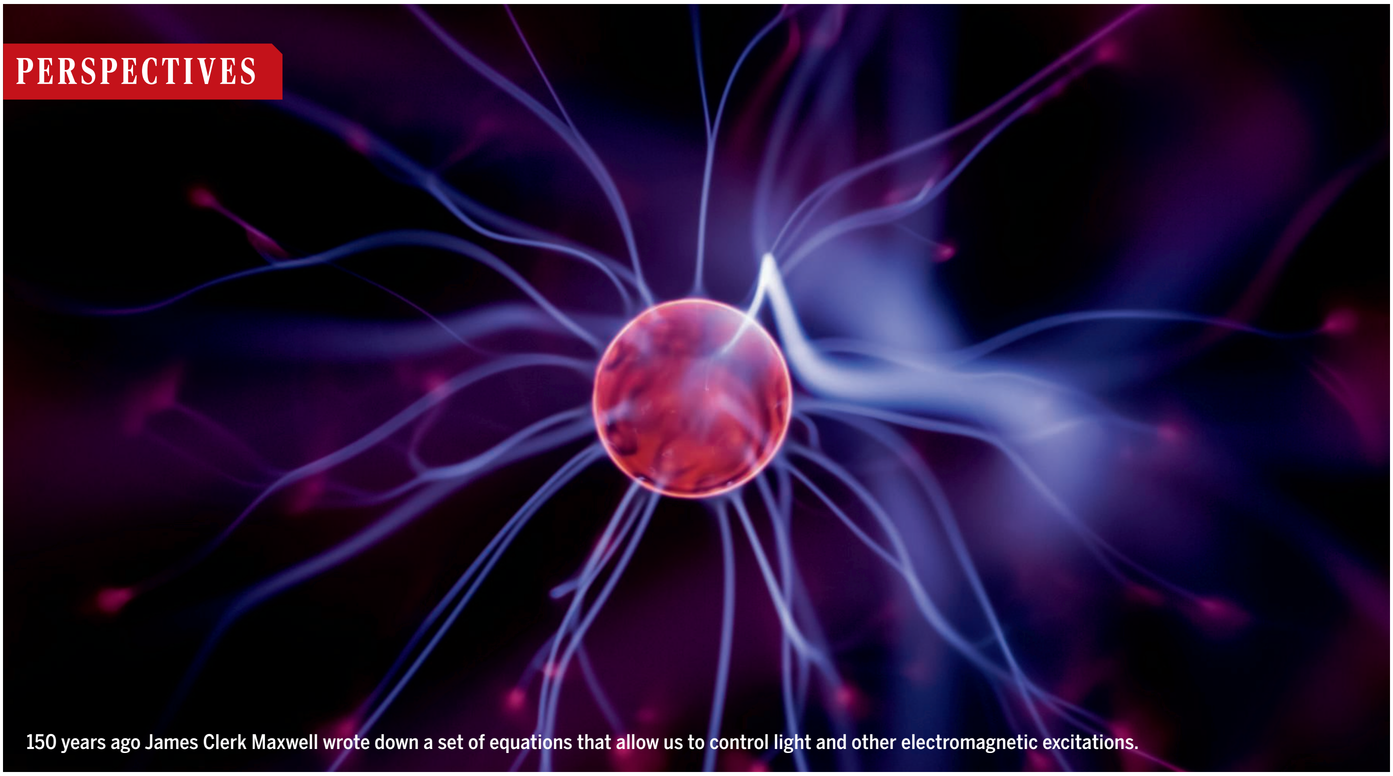
PERSPECTIVES



150 years ago James Clerk Maxwell wrote down a set of equations that allow us to control light and other electromagnetic excitations.

OPTICS

150 years of Maxwell's equations

Powerful tools are available for the manipulation of electromagnetic fields

By **Nader Engheta**

On page 499 of his 1865 paper (*1*), James Clerk Maxwell wrote, "The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws." With that knowledge, he changed the world forever. In the span of 150 years since his celebrated paper, numerous scientific discoveries and technological innovations have originated from Maxwell's equations. Electromagnetic and optical waves can be manipulated, tailored, and controlled by means of materials, and consequently, during the past one and a half centuries, materials science and engineering has always played the key roles in taming these waves for the purpose of inventing new functional devices. Early examples include radio-frequency antennas, lenses and mirrors, microwave waveguides, optical fibers, and telegraph transmission lines, to name just a few. Recent developments in nanoscience and nanotechnology, materials science and technology, and condensed matter physics has made it possible to conceive materials and structures with atomic-level controllability and with unprecedented properties not otherwise present in naturally available materials. These developments have opened doors to numerous opportunities to shape and sculpt light at the nano-, micro- and mesoscales in a desired fashion.

Ushering photons into desired paths requires the design of structures with proper inhomogeneity in material parameters such as permittivity and/or permeability. A good example of such photon traffic control can be achieved with defects within photonic crystals (*2*), where periodic arrays of permittivity variations with photonic band gaps analogous to the electronic band structures for electrons, provide paths for light to propagate (see the figure, panel A). Although bending light has been traditionally done by reflection and refraction of rays through surfaces based on Snell's law, the advent of metamaterials and metasurfaces is now supplying us with transformation optics (*3*) and generalization of Snell's law (*4*, *5*) for tailoring fields at subwavelength scales, opening up possibilities for exciting scenarios such as cloaking, light concentration, optical illusion, and flat photonics. Another paradigm for manipulation of light at the nanoscale is achieved

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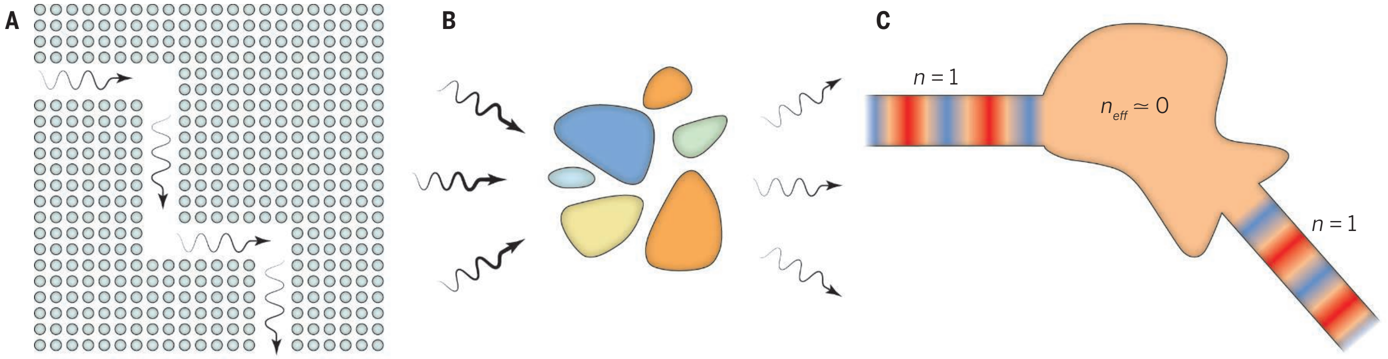
by optical metatronics (*6*), in which deeply subwavelength structures function as "lumped" optical circuit elements (analogous to the resistor, inductor, and capacitor elements in electronics). This unifying circuit paradigm furnishes "common alphabets" between electronics and photonics, allowing transfer of ideas and designs between these two fields. Collections of nanoparticles, when properly designed and suitably juxtaposed, form optical nanocircuits with unprecedented capability of as new platforms for manipulating light. Another extreme scenario is highly confined concentration of light using plasmonic nanoantennas (*10*). Antennas, which have been traditionally used to convert the confined electromagnetic energy in subwavelength regions into the far-field radiation, have been instrumental in the development of numerous fields, such as wireless communications and satellite technology. Shrinking conventional radio frequency antennas into the nanophotonics arena raises For example, two waveguides linked by a near-zero effective-index junction would operate as though they were connected directly to each other (see the figure, panel C). This may have important implication in both classical and quantum optics, in which the distance between two points (two observers, two emitters, or an observer and an emitter), although they may be physically far apart, would behave as if they were close together. This effect will present interesting possibilities for long-range collective emis-



Manipulating electromagnetic fields and waves. (**A**) Photonic crystals as a platform for photon traffic control. (**B**) Optical metatronics, i.e., a collection of nanostructures with properly selected shapes, sizes, and materials, as lumped circuit elements for manipulating and processing optical fields and waves at subwavelength scales. (**C**) "Extreme" metamaterials with near-zero effective refractive index, providing a spatially uniform phase in a bounded region of space that functions as an "electromagnetic point" connecting two distant ports (*12*).

information processing at subwavelength regions (see the figure, panel B). One can then envision designing materials that tailor light-matter interaction in order to perform optical signal processing at the nanoscale, e.g., performing mathematical operations such as differentiation and integration as light passes through such materials and structures (*7*). Perhaps the notion of doing math with light in materials might also be extended to solving equations with light if properly designed nanostructures could be used.

The ability to synthesize materials with desired parameters now offers opportunities to take manipulating the Maxwell equations to the "extreme." For example, two-dimensional materials such as the graphene have brought previously unimaginable possibilities to photonics.

The propagation of highly confined electromagnetic surface waves in the form of surface plasmon polaritons along the graphene sheet has been demonstrated (*8*, *9*), which makes it possible to envision optical devices just one atom thick. Other low-dimensional materials such as hexagonal boron nitride (hBN) and molybdenum disulfide (MoS_2) are also attracting attention the possibility of using suitably designed metallic nanostructures to concentrate light in deeply subwavelength volumes with high field intensity. This has opened new frontiers in detection, sensing, and emission control, such as nanoantenna-enhanced surface-enhanced Raman spectroscopy, and engineering spontaneous emission of quantum dots (*11*).

Adding nonreciprocity to the optics of nanoantennas by using magnetized magneto-optical materials results in phenomena such as near-field optical energy rotation. These effects would be enhanced due to the plasmonic resonance of such nanoantennas and the high intensity of optical fields in their vicinity. This can be a basis for nonreciprocal optical devices, such as circulators, at the nanoscale. As a final example of extreme manipulation of waves, metamaterials with effective parameters near zero bring an entirely new set of mechanisms for tailoring fields and waves (*12*). As relative permittivity and/or relative permeability attain near-zero values in a properly designed metamaterial, the effective refractive index approaches zero, causing the effective wavelength to become very large for the operating frequency. Therefore, the phase of steady-state signals within such a structure is spatially uniform, implying that the structure appears to be subwavelength electromagnetically regardless of its shape and size.

sion, quantum entanglement, and cavity quantum electrodynamics, involving such extreme structures.

James Clerk Maxwell could not have imagined that 150 years later his predicted electromagnetic waves would be manipulated in numerous manners due to developments in science and technology. One would wonder where our world would have been without his ingenious and elegant equations. ■

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