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FEATURE

Taming light at the nanoscale

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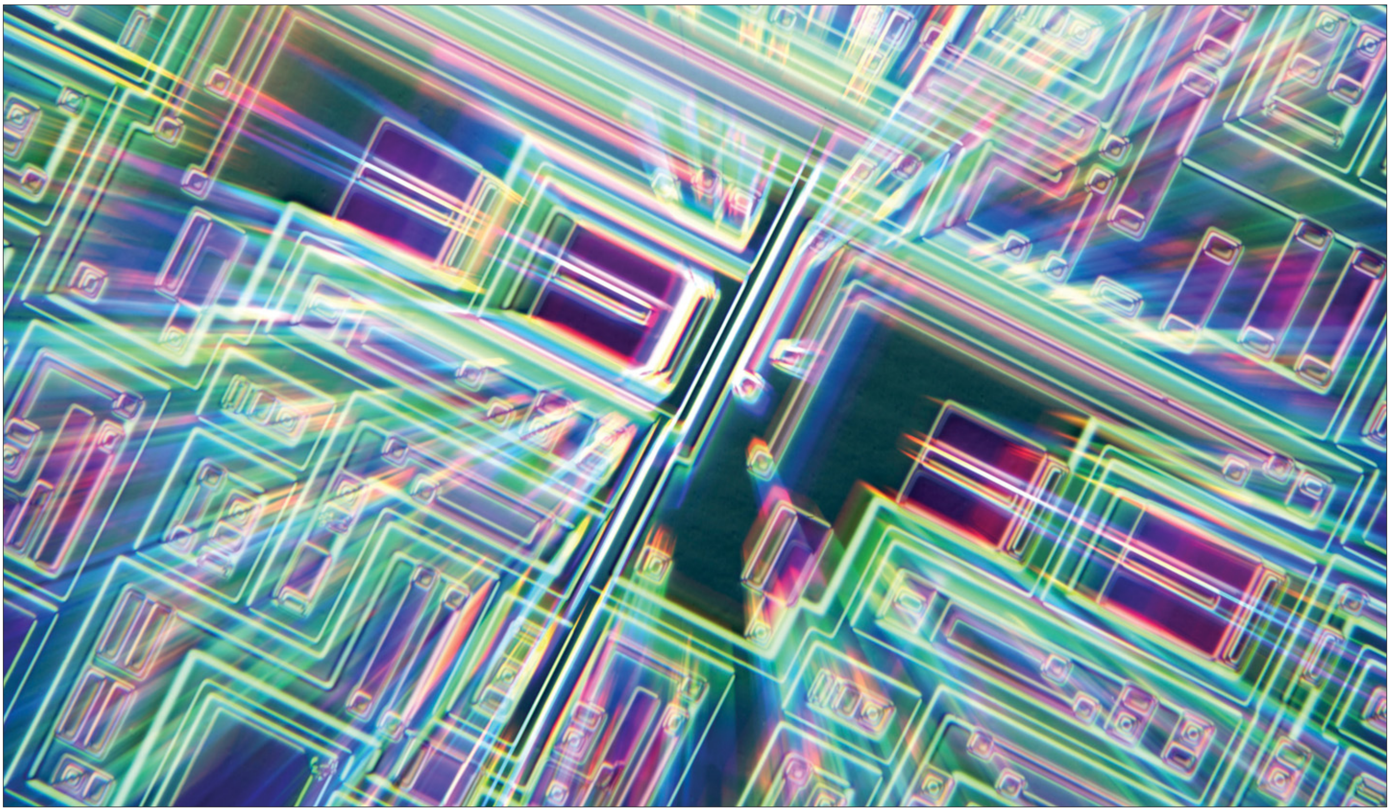

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Taming light at the nanoscale

In electronics we control the motion of charged particles, but is this the only current available to us? **Nader Engheta** describes a new form of circuitry that replaces electrons and wires with light and grooves

Look around, and you will probably see numerous electronic and optical gadgets, such as mobile phones, personal digital assistants, laptops, TVs and digital cameras. These may all do different things but they have one thing in common: in the electronic circuits that drive these devices, charged particles flow through components and impart power via what is known as the conduction current. But is the motion of charged particles the only current we have available?

Those with a good memory for Maxwell's equations of electromagnetism will remember that in addition to the familiar electric field, $\boldsymbol{E}$, there is also a displacement field, $\boldsymbol{D}$, which relates to the effects caused by charges being displaced by $\boldsymbol{E}$. Electronic circuits typically run at radio and microwave frequencies, i.e. 3 kHz–300 GHz, and are usually dominated by the conduction current, which is *directly proportional* to $\boldsymbol{E}$. At terahertz, infrared and visible frequencies of 300 GHz–790 THz, however, the *displacement current* becomes more important. Being simply the time derivative of the vector $\boldsymbol{D}$, i.e. $\partial\boldsymbol{D}/\partial t$, it is proportional to the *frequency* at which $\boldsymbol{D}$ changes direction. The higher the frequency of a circuit's signal, the more prominent its displacement current becomes, and the less significant its conduction current.

It is important to note that the displacement current does not consist of drifting charged particles as the conduction current does. In fact, it is not even confined by metal wires. So how can we tailor and control the electric displacement current $\partial\boldsymbol{D}/\partial t$ spatially and temporally, particularly at the nanoscale, just as we manipulate the motion of charged particles in electronics? The answer lies with metamaterials and plasmonic optics. These novel fields of research can provide us with the exciting tools to tame and manipulate displacement currents at will, allowing us to dream about another paradigm – quite different to but parallel with electronics – in which information is processed by controlling and manipulating the displacement current.

The possibilities for a new form of circuitry that uses displacement current at optical frequencies, rather than conduction current at radio frequencies, are exciting. While conventional electronic circuits, both analogue and digital, have served us well as the driving force behind the development of the modern electronics and information age, the advantage of the displacement current is that it operates at higher frequencies; higher frequency means greater bandwidth, which means that a lot more information can be transmitted. Not only that, but the displacement current offers the potential of circuits that are ultrafast, low power and very small.

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Metananocircuits – what's in a name?

In any form of circuitry, the circuit elements need to be much smaller than their operating wavelengths. A mobile phone, for example, typically operates at frequencies of about 1800 MHz, which corresponds to a wavelength of 17 cm, whereas its antenna is about 1 cm long and individual circuit elements are on the millimetre scale, or even less. For metananocircuits that operate at higher frequencies than this in the optical range, the circuitry needs to be smaller still – on the nanoscale, hence the "nano" part of the name.

As for the "meta" part of the name, it relates to the materials required to construct these circuits. Copper wire may be fine for containing conduction current in electronics, but for displacement current at optical frequencies it does not do the job. Materials are required that can tame the displacement-field current to "flow" and respond in ways analogous to charge flow in electronics. This is achieved using metamaterials: artificially engineered materials formed using collections of building blocks and elements, which are both made from metals and dielectrics. These components are designed and arranged in such a way as to obtain an unusual collective electromagnetic response that is not otherwise found in nature. Such exotic materials have gained much attention as a means of creating "invisibility cloaks".

The field of plasmonic optics is also key here – it addresses the interaction of light with metals, and as such plays a very important role in the field of metamaterials. The concepts of metamaterials and plasmonic optics are both instrumental in enabling us to tame the optical displacement-field currents in metatronics. As electrons play the main role in the field of electronics, and spins in spintronics, here the optical electric field and displacement-field current in metamaterial nanostructures play a relevant role in the field of "metatronics".

What's in a wire?

To make these "metananocircuits", as I have dubbed them (see box above), we have to radically rethink the circuit components, starting from the seemingly simple concept of a wire. As ordinary and mundane as a simple wire is, it serves an important purpose: it is a conduit for the conduction current, keeping charged particles in a given path, even when the wire is bent, twisted and stretched. A wire connecting two points, A and B, restricts the movement of charged particles to between these two points and thus the conduction current is confined within the wire.

However, the displacement current is not usually confined, since wherever you find $\boldsymbol{E}$, even in a vacuum, there is a displacement field, $\boldsymbol{D} = \varepsilon\boldsymbol{E}$, where ε is the permittivity of the local material, representing its electrical response. (It also plays a role in the value of the material's refractive index – a measure of how fast light travels in a material compared with in a vacuum – and is in general a function of frequency.)

In introductory electromagnetic courses, the displacement current is often taught as the time-derivative of the displacement field between the parallel plates of a capacitor (see box on p33). One might conclude from this example that such a field is confined. Indeed, it is true that in this example the displacement current is confined between the two plates of the capacitor. But if we break the capacitor and separate its plates, then the displacement current will no longer stay confined. (Twisting, bending and stretching a metallic wire, in contrast, will leave the conduction current in the wire.) So how can we restrict and confine a displacement current in a given arbitrary path in space, connecting two points A and B, as we easily and commonly do for the conduction current using a simple metallic wire?

Before answering this question, we must understand why charged particles are confined in a metallic wire. They stay there because of the potential barrier between the metal wire and the adjacent material, be it air or plastic, just as water is confined inside a gutter. For the charged particles to pop out of the wire, they need to have enough energy to be able to "go over this barrier", just as water may overflow in a gutter. A metallic wire operating at low frequency has a very high conductivity ($\sigma_{\text{wire}} >> 1$), while the materials outside the wire, i.e. insulators, have a very low conductivity ($\sigma_{\text{background}} << 1$). Since the conduction current at radio frequencies can be written as $\boldsymbol{J}_{\text{c}} = \sigma\boldsymbol{E}$, this huge "mismatch" between the two conductivities results in a very low (practically zero) value of $\boldsymbol{J}_{\text{c}}$ outside the metallic wire, while $\boldsymbol{J}_{\text{c}}$ in the wire stays finite. As a consequence of continuity of currents, the $\boldsymbol{J}_{\text{c}}$ in the wire follows the path of the wire without leaking out, even if the wire is bent, twisted and stretched.

From electronics to metatronics

We would like to create a similar scenario for confining a displacement current, particularly at much higher frequencies. In other words, can we think of a meso-, micro- or nanoscale "structure" that behaves as a "wire" for the displacement current at infrared and optical frequencies, connecting the two points A and B with a displacement current? The answer can be found by comparing the two analogous expressions for conduction current and displacement current: $\boldsymbol{J}_{\text{c}} = \sigma\boldsymbol{E}$ and $\boldsymbol{J}_{\text{d}} = \partial\boldsymbol{D}/\partial t = -i\omega\varepsilon\boldsymbol{E}$. Since the conductivity of a metallic wire is much greater than that of the material outside it, i.e. $\sigma_{\text{wire}}/\sigma_{\text{background}} >> 1$, for the displacement-field current we should analogously search for $\varepsilon_{\text{wire}}/\varepsilon_{\text{background}} >> 1$ at high frequencies. In other words, if we can design a wire-like structure with very high permittivity inside and a very low permittivity outside, then the displacement current $\boldsymbol{J}_{\text{d}}$ would be "trapped" within the structure (figure 1).

But building a structure with very high permittivity at infrared and optical frequencies is not that easy. Another way to make the ratio $\varepsilon_{\text{wire}}/\varepsilon_{\text{background}}$ much greater than one is to choose a "background" or "substrate" material with an extremely low permittivity. But can we have a material with such a very low relative permittivity – or, to use the jargon, an "epsilon near zero" (ENZ)? Yes. There are materials that have a permittivity where the real part is zero (and where the imaginary part is very small), such as silicon carbide operating at a wavelength of about $10.3\,\mu$m. If we need a different wavelength – for example to use the circuit as a sensor for biological molecules that are only sensitive to certain frequencies – we can exploit the notion of metamaterials to engineer a substrate that has an ENZ at another desired wavelength. For instance, it is well known that when we have a stack of thin layers of pairs of materials, one with positive permittivity (e.g. Si_3N_4) and another with negative permittivity (e.g. silver at optical frequencies), the composite structure exhibits an "effective" or bulk permittivity. With the proper choice of layer thicknesses, one can get the real part of the effective bulk permittivity near to zero at a desired wavelength for an electric field polarized parallel to the plane of the stack.

So now we have some choices for a background, but

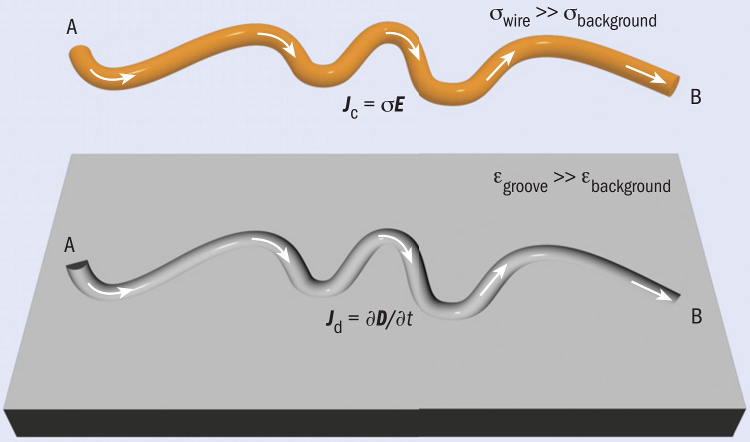
Up to speed with displacement currents

In a dielectric material or metal, the presence of an electric field, $\mathbf{E}$, causes opposite charges to separate, such as atomic and molecular nuclei from their electrons. This in turn induces a displacement field, $\mathbf{D}$, related to $\mathbf{E}$ via $\mathbf{D} = \varepsilon\mathbf{E}$, where ε is the permittivity of the local material. Conduction and displacement currents are defined by $\mathbf{J}_c = \sigma\mathbf{E}$ and $\mathbf{J}_d = \partial\mathbf{D}/\partial t = -i\omega\varepsilon\mathbf{E}$, respectively.

To get a feel for the electric displacement current, imagine a parallel-plate capacitor connected to a sinusoidally time-varying source. In the space between the plates of this capacitor, the electric field changes with time, and thus the vector $\mathbf{D}$ changes with time, and therefore a displacement-field current exists. Such a "current" in the space between the capacitor plates does not involve charged particles being transported across that space. Instead, it is due to the time-varying vector $\mathbf{D}$.

In a time-harmonic electric field, the permittivity ε may in general be treated as a complex quantity with a real and an imaginary part. The real part represents the reactive response of the material and the imaginary part relates to the ohmic loss in the material (voltage drop due to resistance). Materials that have a positive real part, negative real part or a non-zero imaginary part correspond to metananocircuit components (see figure 2).

1 Down to the wire



Wires in electronics (top) and metatronics (bottom). The familiar notion of a wire in electronics is a metallic (or semiconductor) wire embedded in a dielectric (insulating) background. The wire provides a conduit for the motion of charged particles and therefore a path for the conduction current. The huge contrast between the conductivity of the wire and that of its background means that the conduction current is confined in the wire. By analogy, if we have an empty (or dielectric-filled) groove or tube carved in a low-permittivity, or epsilon-near-zero (ENZ), background metamaterial, then the large contrast between the permittivity of the groove/tube and that of its background confines the displacement current to this groove, or "$\partial\mathbf{D}/\partial t$ wire". Such a wire is one of the building blocks of the paradigm of metatronics, promising the possibility of all-optical information processing at the nanoscale.

what about a conduit for the displacement current itself? Suppose, in an ENZ substrate, you cut an arbitrarily shaped groove or tube between two points A and B, and filled it with air, or any material with conventional permittivity. One would then obtain a channel in which the permittivity is relatively very large compared with the permittivity of the substrate, i.e. $\varepsilon_{\text{groove}}/\varepsilon_{\text{background}} >> 1$. So when a displacement current is induced in this groove at point A, it must "follow" the groove and "get" to point B, since it cannot leak into the ENZ substrate where $\mathbf{D} = \varepsilon\mathbf{E}$ must be zero. Indeed, this groove would act as a "wire" for "connecting" points A and B using the displacement current, when operating a circuit at high frequency.

At infrared and visible frequencies, this analogous "$\partial\mathbf{D}/\partial t$ wire" may provide an exciting alternative to the standard metallic wires for conduction currents, which work well at low frequencies. Despite this analogy, there are, of course, some differences between the two scenarios. For the conduction current, we need charged particles with an effective mass to drift along in the wire, whereas for the $\partial\mathbf{D}/\partial t$ wire it is just the vector field $\mathbf{D}$ in the groove/tube that "connects" one point to the other – no charged particle is transported in the groove.

Making metatronic circuits

With the notion of a $\partial\mathbf{D}/\partial t$ wire in hand as a platform to tailor and manipulate displacement current, let us see what we can do with such a wire. First, we can make an optical $\partial\mathbf{D}/\partial t$ wire in the shape of a circuit at the meso-, micro- or nanoscale by carving a hollow tube (or a groove) in an ENZ substrate (figure 2). If a source of optical radiation that radiates like a small dipole – such as a quantum dot, fluorescent molecule or optical nanoantenna – is placed inside this groove, then under suitable conditions the optical mode with a longitudinal vector $\mathbf{D}$ may be induced, thus producing a displacement current that is confined within the groove. The optical dipole source powers the metananocircuit with light in an analogous way to how a battery or a radio-frequency source powers an electronic circuit with electrons.

In one of my research group's recent papers (A Alu and N Engheta 2009 *Phys. Rev. Lett.* **103** 143902) we show a series of numerical simulations for 2D air-filled grooves carved into a substrate with effective-ENZ properties, while a dipole source is located in these grooves. The numerical simulations for the distribution of the electric field show that it is primarily longitudinal along the grooves, following the path of the air-filled structures. We do have electric field outside the groove as well. However, when we consider the vector $\mathbf{D} = \varepsilon\mathbf{E}$, we notice that $\mathbf{D}$ is non-zero only inside the air-filled groove and zero in the ENZ substrate. The substrate acts as an optical "circuit board" for the displacement current, and it can function at optical frequencies and at nanometre scales. So, we have now found a way to confine and manipulate the displacement current in an arbitrary path and have a $\partial\mathbf{D}/\partial t$ nanoscale circuit that is driven by light.

Optical circuit components

What can we do with such $\partial\mathbf{D}/\partial t$ wires and optical nanocircuit boards? In conventional electronics we connect wires to circuit elements such as capacitors, inductors, resistors, transistors and diodes. But can we extend this notion of lumped circuit elements to optical frequencies using the displacement current instead of conduction current? In other words, can we come up with deeply sub-wavelength nanostructures that may behave as optical versions of capacitors, inductors and resistors when exposed to optical signals?

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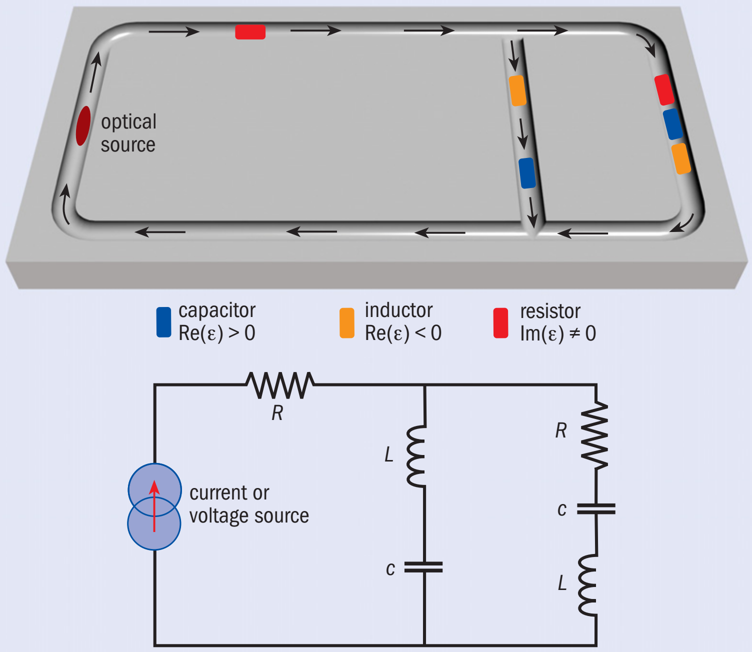
2 Metananocircuits



Optical nanostructures made out of suitable materials can be used as lumped circuit elements in $\partial \boldsymbol{D}/\partial t$ wires (top). The trapped optical displacement-field current connects the nanoelements, which have functionalities resembling those of resistors, inductors and capacitors in radio-frequency electronic circuits (bottom). The optical displacement current follows the closed paths, forming a metatronic circuit in which the displacement current is the important entity that can be manipulated. The analogy between metatronics in nano-optics, and electronics at radio-frequency wavelengths provides a powerful tool for designing novel nanophotonic circuitry with numerous applications in optical information processing, data storage, molecular spectroscopy and nanoscale metrology, to name just a few.

The answer is "yes", and my research group has studied this concept in recent years (N Engheta 2007 *Science* **317** 1698). We have been developing the notion of metamaterial-inspired optical circuits at the nanoscale, for which we now use the term "metatronics". Here, properly designed and arranged sub-wavelength nanoparticles can indeed act as such localized nanoscale optical capacitors, inductors and resistors, when their material permittivity has a positive real part, negative real part or non-zero imaginary part, respectively.

If we can treat optics as circuits, we can potentially bring the whole machinery and mathematical tools of circuit theory and designs – which have been studied for decades – into the field of nano-optics. Imagine, for example, putting a collection of nanoparticles with specific shapes and materials into the air-filled tubes or grooves carved in an ENZ substrate (figure 2). This would become an optical metatronic circuit, in which the optical $\partial \boldsymbol{D}/\partial t$ wire "connects" these nanoparticles as localized optical circuit elements. When such a metatronic circuit is excited by an optical signal, a pattern of local optical electric fields and optical displacement currents is produced – analogous to the pattern of voltage and current distributions in a conventional radio-frequency circuit. This patterning of the local optical field can, under the proper conditions, provide us with functionalities for information processing: in the same way that an electronic circuit may exhibit certain functionalities, such as acting as a band-pass filter, here we would also have an optical nanocircuit that would function as a nanoscale filter with light. This would provide us with a new form of circuitry – a new paradigm for information processing.

Promising possibilities

As part of our recent efforts, my research group and I have developed several concepts that would put metatronics to novel use. These include nanofilters, nanoscale optical barcodes and Yagi–Uda optical nanoantennas (essentially very small versions of standard TV antennas) for manipulating molecular emission and absorption. Also intriguing are the ideas of far-field subdiffractive optical microscopy and hyperlenses, tuning and matching optical nanoantennas, optical wireless systems at the nanoscale, optical nanotransmission lines and negative-refraction photonic metamaterials, to name a few.

The possibilities of metatronics are immense, not least because they may suggest new ways of tackling nano-optical data processing. It could lead to the fields of circuit theory and design merging together with nano-optics, using the tools of metamaterials and plasmonics to achieve this. It may offer exciting possibilities for nanoscale computation, data storage, information processing and other functionalities. These circuits may be comparable in size to biological entities – with dimensions at sub-optical wavelengths. They could therefore, some day be "interfaced" with collections of biological elements, such as molecules, and might lead to the coupling of metatronics and molecular electronics. Perhaps some of these molecules or cells may themselves be considered as optical "nanoelements" or "microelements" in such circuits, or conversely, the optical metatronic circuits may "load" and "wire up" biological nanoelements (like loading a cavity resonator), causing changes in the optical spectroscopy of such molecules. Perhaps such metatronics will one day provide a new interface with biological nanostructures and offer the required impedance match between the worlds of optics and biology. Moreover, this paradigm of metatronics may also facilitate the connection between the nanoworld and our macroworld.

Needless to say, there are challenges ahead. These include the nanofabrication of specifically designed metatronic circuits, and real-time detection of signals at various nanoscale locations in such circuits. For this detection, one would need to use near-field scanning optical microscopes, effectively acting as optical voltmeters and ammeters at the nanoscale. For more complex circuits, components with functionalities beyond resistors, capacitors and inductors are required, so 2-, 3- and possibly *N*-terminal elements need to be developed; a metatronic transistor would need three or more terminals in analogy with electronic transistors.

But then, the new paradigm of metatronics offers the potential for ultrafast, low-power, high-bandwidth, and deeply miniaturized circuitry. Moreover, it would be exciting to explore the part that quantum effects will play as the size of metatronic circuits shrinks even further. As is the case for any new territory, the challenges are tough, but many of us are confident that these will be outweighed by far when the promises of metatronics come to fruition. ■