METAMATERIALS

A stamp of quality

Transfer printing of negative-index metamaterials with areas of tens of square centimetres onto flexible substrates paves the way for practical, low-cost, large-area exotic optics.

Richard D. Averitt

A mirage in the desert and the apparent bending of a straw in a glass of water both arise from the passage of light through materials with spatially varying refractive indices. The refractive index sets the speed of light in a particular material, and describes how light changes its direction when passing between materials. During the past decade, the advent of metamaterials — that is, artificial materials with periodic nanoscale structures — has extended our control over refractive index into new regimes, including that of negative values not found in nature, and has enabled remarkable applications such as cloaking[1,2]. However, illusions such as the bending of straws and cloaking both require control over the refractive index of large amounts of matter.

Therein lies a major challenge: a metamaterial gains its special properties by virtue of structures with spatial scales of hundreds of nanometres or less, but areas of a square centimetre or more will be needed for many real applications. This contrast requires us to push the limits of nanoscale fabrication, particularly to control refractive indices at infrared wavelengths or shorter. Now, writing in *Nature Nanotechnology*, John Rogers and colleagues[3] at the University of Illinois at Urbana-Champaign report a transfer printing method capable of creating large-area metamaterials that have a negative index of refraction in the infrared.

The crucial first step is the fabrication of a reusable stamp (Fig. 1a), which eliminates the need to recreate subwavelength features from scratch every time the metamaterial is fabricated. This drastically increases throughput and lowers fabrication costs relative to techniques such as electron-beam lithography. Rogers and colleagues[3] make their stamp by sculpting a fishnet pattern from silicon wafers using soft lithography techniques, combined with etching. The stamp is then 'wetted' with an ink.

The ink consists of eleven alternating layers of silver and magnesium fluoride blanket-deposited over the stamp, with a total thickness of nearly half a micrometre.

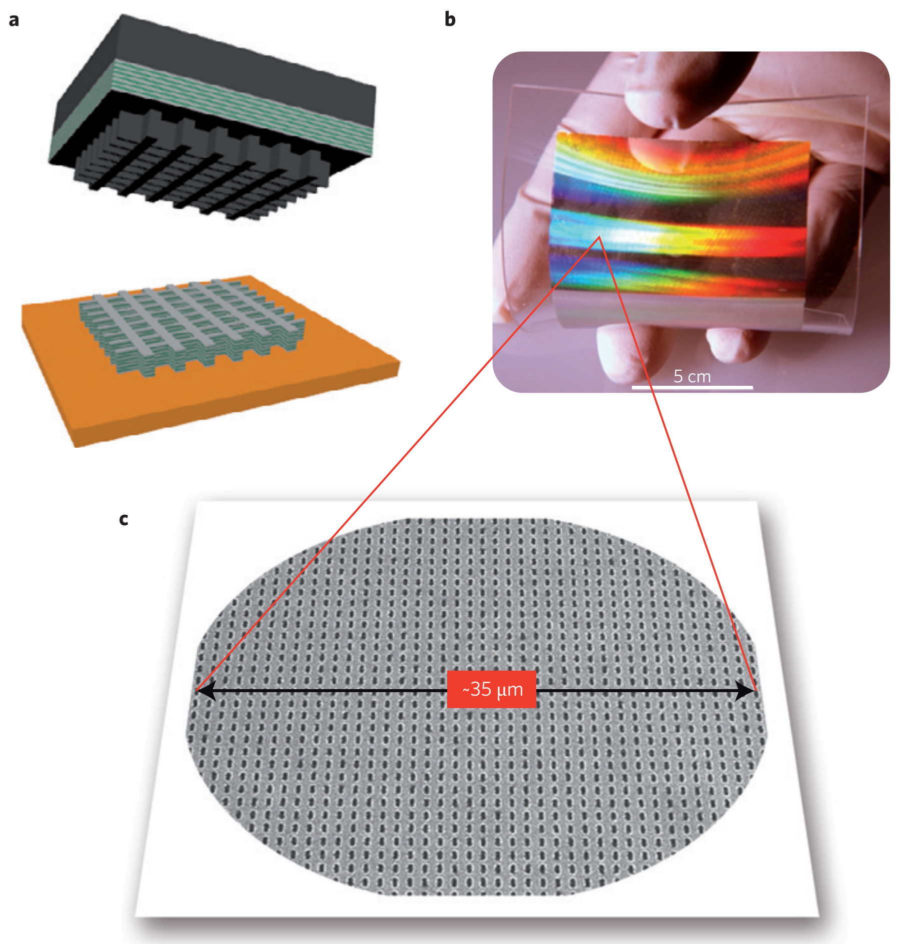

Figure 1 | Nanotransfer printing of metamaterials. **a**, A reusable nanopatterned stamp is used to transfer a thin film to a substrate. **b**, Photograph of a finished metamaterial film, which has an area of the order of square centimetres and a negative index of refraction in the infrared. **c**, Expanded view of the metamaterial showing a fishnet patterning. Figure adapted from ref. 3.

The material composition and individual layer thicknesses of the stamp are chosen to produce a negative refractive index for infrared light, so that light passing from air into the material bends in a direction opposite to the direction it would bend were the refractive index positive. The stamp features are made deeper than the ink thickness to prevent smearing and loss of detail. Once inked onto the stamp, the metamaterial film can be transferred onto a supporting substrate, and the stamp cleaned and reused.

Rogers and colleagues[3] succeeded in creating metamaterial structures with lateral dimensions of 10 cm × 10 cm, supported on a flexible substrate (Fig. 1b). Optical reflection and transmission spectroscopy revealed a high degree of uniformity over the entire metamaterial, implying little variation of structural features. This is impressive given that the smallest of these features were only 500 nm in size, corresponding to a micrometre unit cell (Fig. 1c). More than ten billion cells are present in the 10 cm × 10 cm metamaterial pictured in Fig. 1b.

To put this work in perspective, it is important to realize that the field of metamaterials is only a decade old, with the first convincing demonstration of a three-dimensional metamaterial with a negative refractive index (at near-infrared wavelengths) being reported as recently as 2008[4]. That groundbreaking work, by Xiang Zhang and colleagues at Berkeley, used a structure very similar to the one used by the University of Illinois team[3], except that it was fabricated using focused ion-beam milling and had overall lateral dimensions on the micrometre scale. Rogers and colleagues have literally extended this work by creating a metamaterial with macroscopic lateral dimensions. It is important to note, however, that dimensions in the propagation direction are of the order of a single wavelength. These metamaterials are thin films, analogous to a drop of oil on water rather than a cup full of water.

It is often remarked that the phenomena that metamaterials make possible are, to first order, scale invariant. Unfortunately, this tenet does not extend to fabrication, and different regions of the spectrum require different fabrication strategies[5]. Achieving metamaterial effects at even relatively long wavelengths (in the microwave-to-terahertz part of the spectrum) will require additional advances in three-dimensional fabrication. Nanotransfer patterning is unlikely to play a role in such advances because the individual unit-cell dimensions are typically tens of micrometres or larger. However, one can imagine multiscale metamaterials derived from combining transfer patterning with other fabrication approaches. Transfer printing can also be applied to perfect absorbers, to devices based on transformation optics (such as cloaks and concentrators) and to plasmonic devices.

The work by the University of Illinois team[3] suggests that metamaterials research is entering a new phase, with the focus shifting — in part — from proof-of-principle laboratory demonstrations to the development of practical fabrication strategies that enable real-world applications. Work of this variety is crucial if the full potential of metamaterials is to be realized. As a parallel, consider the development of fibre optics. After initial demonstrations, years of hard work were required to create glass of sufficient purity to reduce propagation losses to the levels required to enable the telecommunications boom[6].

In summary, if metamaterials are to move beyond concept to application, the production of large-area, high-fidelity metamaterials at low cost should be a priority. Rogers and colleagues[3] have taken an important step in this direction. Indeed, the pace of discovery and advancement in metamaterials research suggests a promising road ahead. ❐

Richard D. Averitt is in the Department of Physics, Boston University, 590 Commonwealth Avenue, Boston, Massachusetts 02215, USA.
e-mail: raveritt@bu.edu

References

1. Shelby, R. A. *et al. Science* **292,** 77–79 (2001).
2. Schurig, D. *et al. Science* **314,** 977–980 (2006).
3. Chanda, D. *et al. Nature Nanotech.* **6,** 402–407 (2011).
4. Valentine, J. *et al. Nature* **455,** 376–379 (2008).
5. Fan, K. *et al. Opt. Express* **19,** 12619–12627 (2011).
6. Schultz, P. C. *Opt. Photon. News* **21,** 30–35 (October 2010).

NANOBIOTECHNOLOGY

Building a basic nanomachine

Attaching certain protein fragments that are found in the nuclear pore complex onto a solid-state nanopore mimics important aspects of the selective transport of molecules and proteins that occurs in real cells.

Tijana Jovanovic-Talisman and Anton Zilman

"What I cannot create, I do not understand." This phrase, attributed to Richard Feynman, epitomizes the drive to create biomimetic devices using nanotechnology. Writing in *Nature Nanotechnology*, Roderick Lim, Cees Dekker and colleagues[1] report the creation of a minimalistic nuclear pore complex (NPC) by assembling biological and synthetic components into a geometry that resembles the real NPC. The synthetic device shows NPC-like selectivity on the single-molecule level, and provides new insights into some important and still debated aspects of the NPC structure.

In every eukaryotic cell, the DNA and proteins in the nucleus are separated from the rest of the cell (the cytoplasm) by the nuclear envelope; this barrier keeps the transcription of DNA into RNA inside the nucleus, and keeps the translation of RNA into proteins in the cytoplasm. NPCs are multiprotein biological nanomachines that perforate the nuclear envelope and gate all transport between the nucleus and the cytoplasm, ensuring proper cellular function. The central feature of this complex is a region of unfolded proteins containing phenylalanine–glycine repeats (FG Nups) that line and partly occlude the channel on both the cytoplasmic and the nucleoplasmic side of the pore (Fig. 1a). Small molecules pass through the NPC freely, whereas larger molecules are selectively carried through by specialized transport proteins, such as Importin-β, that bind weakly and transiently to the FG Nups.

The translocation of these transport proteins and their cargoes through the NPC essentially occurs by diffusion that is controlled by the interactions with the FG Nups. Despite the nonspecific interactions with the vast background of molecules inside the cell, this transport is highly selective. During the past decade, a wealth of information has been gathered for the approximately 30 different proteins that constitute the NPC, including their *in vitro* behaviour and their assembly into a structural scaffold[2–5]. Bulk and single-protein transport rates have also been reported *in vitro* and *in vivo*[6–8]. Although several models have been proposed, we still do not understand how the rate and selectivity of transport through the NPC can be mechanistically linked to the conformation and the dynamics of the FG Nups (see review in ref. 6).

However, it has been suggested that the most essential functional features