anomalous properties. Nevertheless, this doesn't hinder the validity of the model because it should remain applicable for metamaterials having the properties as specified by Nicolaou and Motter.

Applications for materials exhibiting negative compressibility are typically associated with structures where it is desirable that compression is to be avoided, such as telecommunication lines or sensors present in high-pressure environments such as those found in deep oceans[2]. Owing to its different underlying mechanism, the metamaterial proposed by Nicolaou and Motter should also exhibit force-amplification transitions, which means that it could be used in microelectromechanical systems or actuators — if this hypothetical structure can be implemented in practice. Nevertheless, as the occurrence of negative compressibility is quite rare, the work of Nicolaou and Motter may further stimulate studies in a field that is still far from being exhausted. More mechanisms that give rise to negative compressibility may be suggested based on the approach taken by the researchers. Such advanced studies could deepen the knowledge of negative-compressibility systems and explore new means of exploiting such materials for hitherto unimagined applications. ❐

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References

1. Nicolaou, Z. G. & Motter, A. E. *Nature Mater.* **11,** 608–613 (2012).
2. Baughman, R. H., Stafstrom, S., Cui, C. & Dantas, S. *Science* **279,** 1522–1524 (1998).
3. Fortes, A. D., Suard, E. & Knight, K. S. *Science* **331,** 742–746 (2011).
4. Lakes, R. S. & Wojciechowski, K. W. *Phys. Status Solidi B* **245,** 545–551 (2008).
5. Gatt, R. & Grima, J. N. *Phys. Status Solidi Rapid Res. Lett.* **2,** 236–238 (2008).
6. Grima, J. N., Attard, D., Caruana-Gauci, R. & Gatt, R. *Scripta Materialia* **65,** 565–568 (2011).
7. Barnes, D. L., Miller, W., Evans, K. E. & Marmier, A. S. H. *Mech. Mater.* **46,** 123–128 (2012).
8. Poźniak, A. A. *et al. Rev. Adv. Mater. Sci.* **23,** 169–174 (2010).

MATERIAL WITNESS

AGAINST THE FLOW

PHILIP BALL

It seems inevitable that the manipulation of light and sound with metamaterials[1–3] — in which the 'atoms' are themselves artificial composites of other materials — should lead sooner or later to notions of manipulating heat. These are of course not equivalent — the heat equation is not the wave equation — but there are evident analogies. In particular, the key to controlling the flow of energy in each case is anisotropy. If transmission differs in different directions, then a prescribed path for the flow can be engineered with a suitable arrangement of materials. It is this, for example, that has enabled optical invisibility shields to be manufactured from simple, suitably shaped birefringent crystals[4].

The possibility of using a gradient in thermal properties to produce counterintuitive heat flows, including a flow from cold to hot (that is, apparent negative thermal conductivity) was first adduced by Fan and co-workers[5]. Now such notions have been experimentally realized by Narayana and Sato, who have made metamaterial composites that can guide heat flux along all manner of non-intuitive paths, including a reversal of the heat current[6].

The basic design element used by Narayana and Sato is a tube of metamaterial embedded in a slab of host material through which heat passes from a hot to a cold side. The tube is designed to generate a particular heat profile in the interior. The metamaterial is conceptually simple: a multilayer of two alternating materials with different (isotropic) thermal conductivities. The thermal properties of the composite are different parallel and perpendicular to the layers.

First, then, a thermal shield. Of course, crude thermal insulation — lagging a pipe, say — is already a kind of shield. But not only does this provide, at best, only partial insulation from the thermal gradient outside, it tends also to significantly perturb the external temperature profile. In contrast, the thermal shield described by Narayana and Sato actively equalizes the internal temperature by rerouting heat flow, while leaving the external profile untouched. It's the same distinction as between an opaque box and a true invisibility cloak.

The shield is a series of concentric cylinders of latex rubber and a silicone elastomer with ceramic particles dispersed in it. These materials are chosen for thermal conductivities that minimize the contrast with that of the host material, a block of agar gel. Meanwhile, layers arranged radially rather than concentrically in the tube wall act as a 'thermal concentrator' that creates a central region of enhanced, but uniform, energy density.

Finally, and most dramatically, when the layers are arranged in spirals, they twist the heat flux into a 'yin–yang' form so as to invert the thermal gradient in the inner region.

Reversing the flow of heat sounds like reversing the second law of thermodynamics — a manifestation of Maxwell's demon. But of course it is not, any more than a negative refractive index violates the laws of optics. Rather, this is another demonstration that creative arrangements of materials can seem to transcend their own fundamental limitations: a reminder that the laws of physics mustn't be confused with their apparent consequences. ❐

References

1. Chen, H., Chan, C. T. & Sheng, P. *Nature Mater.* **9,** 387–396 (2010).
2. Cui, T. J., Smith, D. R. & Liu, R. (eds) *Metamaterials: Theory, Design, and Applications* (Springer, 2010).
3. Cummer, S. A. *et al. Phys. Rev. Lett.* **100,** 024301 (2008).
4. Chen, X. *et al. Nature Commun.* **2,** 176 (2011).
5. Fan, C. Z., Gao, Y. & Huang, J. P. *Appl. Phys. Lett.* **92,** 251907 (2008).
6. Narayana, S. & Sato, Y. *Phys. Rev. Lett.* **108,** 214303 (2012).