EE Times: *But isn't free space defined as having an index of refraction equal to 1?*
Schurig: Yes, but in this case we don't need negative values. We just need values between 0 and 1. Metamaterials research has already shown that negative indices are difficult if not impossible to do with natural materials. But it is also true that indices of refraction that are positive, but less than one, are just as difficult to achieve in natural materials as negative values, and for the same reason: Both cases require a resonance, and in traditional materials the resonance is seldom where you want it to be. But with engineered composites, or metamaterials, you can put the resonance where you want it.

EE Times: *A resonance at the working frequency, here at the wavelength you are trying to cloak?*
Schurig: Yes. It's relatively easy to engineer a metamaterial that has the correct permittivity, permeability and anisotrophy you need at every point to cloak something, but it's hard to imagine doing that with natural materials.

EE Times: *The metamaterials I'm familiar with work on microwaves and use circuit boards with split-ring oscillators on them to provide resonance at the working frequency. Is that the setup you are proposing too?*
Schurig: Yes, that is mostly what we do here. In fact, our first demonstration of a cloak will use those same circuit-board-based materials.

EE Times: *Are you going to build a real working cloak?*
Schurig: As you might guess, we are working on that right now.

EE Times: *I am guessing that your first real cloaking device will provide a smooth transition effect around a known volume at microwave frequencies. Is that the case?*
Schurig: Yes.

EE Times: *Even that's got real applications. For example, why couldn't you use one of those to cloak a spy satellite to keep radar from finding it?*
Schurig: Absolutely. Hiding from radar is an application where metamaterials are already working in the right frequency range. Visible light, for sure, is on the order of 10 years off, but using [a cloaking device] to hide from radar could be much sooner.

EE Times: *For your initial experiments in the microwave range, how big a volume are you going to try to cloak?*
Schurig: Well, our measuring apparatus is only designed to measure things on the order of tens of centimeters.

EE Times: *So you will start with a volume that measures less than 100 centimeters on a side?*
Schurig: Yes, our demonstration cloak will be on that kind of size scale.

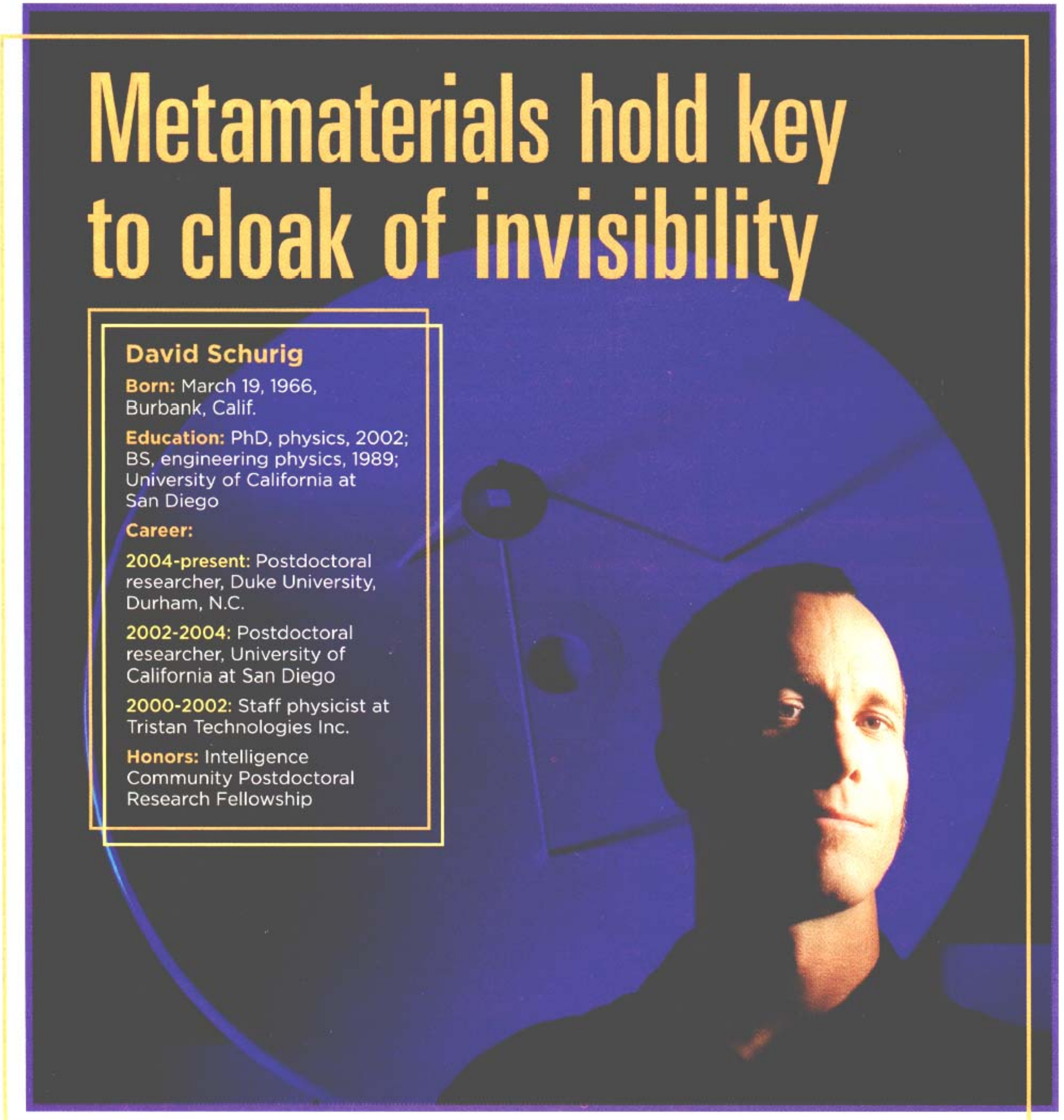
EE Times: *When do you expect to finish it?*
Schurig: Originally we were telling people about a year, but things are going pretty well, so now we expect to have a demonstration substantially sooner than that.

EE Times: *What advice do you have for EEs who might be interested in experimenting with cloaking?*
Schurig: A big part of the design process here keeps harking back to basic circuit models. Those models that EEs learned in school are very powerful--we use them over and over again to design our metamaterials. Just intuitively, when you think about a metamaterial's split-ring resonators, you think about changing their properties by changing the inductance and capacitance of the split rings, which changes their resonant frequency.

EE Times: *Does this mark a resurgence of basic electronic-engineering skills, but applied at a different size scale?*
Schurig: We think so. Most of us are physicists here, but we are using the EE's basic circuit models all the time. In fact, we are all working in the EE department here at Duke.

EE Times: *After perfecting these circuitry principles at the scale of circuit boards for microwaves, do you expect these structures to then migrate down to microelectromechanical systems?*
Schurig: Yes, I think that will happen over the next 10 years. Getting them down to the nanoscale will enable cloaks to work at visible-light frequencies.

EE Times: *The cloaking effect is always going to be limited in bandwidth--tied to a frequency range. But could there be some way to use three parallel systems, like RGB, to make a cloak work for the whole range of visible light?*
Schurig: Yes, that's possible, or a single system could be dynamically adjustable too. There are lots of little tricks that engineers will be able to play.
If EEs are interested in these cloaking devices, then I suggest that they start learning about metamaterials today. That's the technology that is going to make the cloaking device a reality.



A cloak of invisibility: It sounds like the stuff of comic book superheroes. In fact, invisibility cloaks for any type of electromagnetic radiation--even visible light--are something Duke University postdoctoral fellow David Schurig believes are within grasp. Schurig and the professors directing his research--David Smith at Duke and Sir John Pendry at the Imperial College in London--maintain that by the end of 2007, metamaterials will enable an invisibility cloak that works in the microwave range. Further engineering effort will create such cloaks for other types of light, the researchers say.

Metamaterials, or engineered composites, substitute macroscopic objects for atoms in a giant crystalline-like lattice, enabling the pitch of passive-component arrays to set the wavelengths affected. The design of these component arrays harks back to the first principles of electronics--simple R-C-L (resistor-capacitor-inductor) circuits. The electromagnetic waves passing through arrays of tiny resistors, capacitors, inductors and other dielectric materials positioned in free space can be bent down any designer-specified path.

In 2000, Smith, who was then at the University of California- San Diego, and his colleagues demonstrated a composite metamaterial that used embedded passive resonators to bend microwaves backward. The circuit elements that the team used were based on the theoretical analysis provided by Pendry and his colleagues in London.

Schurig recently sat down with technology editor R. Colin Johnson to describe how the cloaking device works, and what EEs can do to turn this science fiction idea into fact.

EE Times: *Where did the cloaking concept originate?*

David Schurig: The cloaking concept came from Sir John Pendry's 1996 paper with Andrew Ward. That work simplified finite-element codes by taking a complicated geometry and transforming it into a simpler geometry before doing simulations--this was before commercial codes made meshing so easy. What Pendry realized, just last year, was that the material properties that he and Ward used in these fictitious spaces were realizable now, thanks to this new field of metamaterials.

EE Times: *So it was a decade--from 1996 to 2006--between Pendry's seminal paper and the cloaking device research that he collaborated on with you and professor David Smith at Duke?*

Schurig: Yes. John [Pendry] imagined this strange space that can be curved or twisted or bent, or even have holes in it to hide things. What his new theory told us was how to construct materials that make our normal space behave the same way as this hypothetical space.

EE Times: *How should EEs imagine these transformations?*

Schurig: They should imagine a piece of cloth woven with a hole in it made by pushing a pointed object between the threads without tearing them. This hole is where you hide something in the two-dimensional space. Electromagnetic fields are confined to move along the threads, and can never access anything hidden in the hole.

Of course, the trick is to come up with the material properties that make our normal space, which doesn't have holes in it, behave as if it did. To do that, you take a mathematical description of how the distorted thread pattern differs from the normal weft and weave of the cloth. This is the coordinate transformation. Then you ask, is there a set of material properties that will give the same form for Maxwell's equations as you find for them under this coordinate transformation?

Those material properties make electromagnetic fields in our boring, flat, hole-free space behave as they do in the much more interesting, distorted space.

EE Times: *Maxwell's four differential equations summarize all the properties of electromagnetic fields. So I guess you guys spent the last year learning how to transform them to handle odd-shaped spaces?*

Schurig: Pendry did the first couple of transformations himself, then he started to talk to David [Smith] and me about it, and we all agreed that it was pretty interesting. So we started doing more transformations. Then I wrote some ray-tracing code to give independent confirmation that these things really do behave the way the theory says they are supposed to.

And that all proved out. Since then, another professor here, Steve Cummer, has done full-wave simulations using Maxwell equation solvers. Those also worked without a hitch, which to us was very surprising, because for the light to go around an object and still be in phase on the other side, you would think it would have to exceed the speed of light.

EE Times: *I've read about that. The light has to travel a longer distance than usual around the outside of the cloaked region, and since by definition it is already traveling at the speed of light, the extra distance would mean it had to go even faster to stay in phase with the light in the surroundings. But it doesn't really transport energy faster than the speed of light, does it? Doesn't it really just use stored energy built up in the steady state to make one specific frequency's phase fronts exceed the speed of light?*

Schurig: That's right. You've done your homework. You have a good understanding of dispersion and relativity--that's exactly it. But it's not as hard as it sounds. Remember, it's easier to hide things from the human eye than [from] a spectrometer [laughs]. The eye only sees in three bands [red, green and blue], and there are all kinds of ways to trick it. The easiest way is when the environment is monochromatic, like in a jungle setting where most everything is bathed in green light; there you could do very well, even though your cloak has limited bandwidth.

EE Times: *Don't these metamaterials work only for long wavelengths, such as microwaves? Are metamaterials available for the visible region today?*

Schurig: Metamaterials do not currently work on visible light; that's probably 10 years off. But in principle, it's possible.

EE Times: *I can imagine making a traditional lens-and-projection system to route visible light around an object. Why, in principle, do you need metamaterials at all?*

Schurig: For one thing, the specifications that come from the transformation theory require that the material be both inhomogeneous, meaning its properties need to vary from point to point, and anisotropic, meaning that the properties depend on the orientation of the fields, too. And finally, you also need materials [with] permittivity and permeability that are less than that of free space.

EE Times: *Is that where the negative index of refraction comes from? Permittivity and permeability are measures of a material's capacity to form electrical and magnetic fields inside it, respectively. Aren't both always positive for natural materials, meaning that the response of the material is always in phase with applied fields?*

Schurig: Usually, yes, but for an invisibility cloak we don't need negative values, just values that are smaller than free space.