Terahertz Pioneer: Sir John B. Pendry

"Theoretical Physics for a Practical World"

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SIR JOHN PENDRY[1] leaves one with the impression of being in the presence of a person of quiet determination, with the resolve to take on challenges that would place most scientists well out of their comfort zone. Although a theoretical physicist by degree, his early training, and whatever free time he had in his youth, were spent on a wide variety of experimental endeavors. These included electronics, chemistry, wireless, and solid-fuel rockets, which he was able to launch, *cows and sheep notwithstanding*, from the farms surrounding his family home in Manchester, U.K. His parents ran a Sweet Shop (one can only imagine the delight this must have been to a young lad growing up in the deprivations of WWII England), with a cellar in which he could do his experiments. John's uncle was an engineer by training and taught in a local school. He often brought John to the school lab, unquestionably influencing his early leanings towards science.

John attended an ordinary grammar school, but insists that his training was extremely rigorous. It must have been, because he entered Downing College, University of Cambridge, U.K., in 1962, and completed his bachelor's degree in 1965. Although John wanted to read theoretical physics, it was not offered as a stand-alone degree at Cambridge. Instead, drawing on his youthful experiences in the Sweet Shop cellar, he majored in experimental physics. When it was time to move on towards a PhD, a "not-so-impressive" showing on the final exams of his senior year put him into a very awkward position. Fortunately, the recognition by John's tutors at Downing that he was a person who could work competently and independently, along with a helping hand from Sir Nevill Mott (Director of Cavendish Laboratory and 1977 Nobel Laureate in Physics), secured Pendry a research fellowship at Cavendish with Mott's former student, Volker Heine. Heine, who felt at the time that he was taking a gamble on this questionable student, later commented on how well the bet had paid off.[2]

SIR JOHN PENDRY

Heine, who was running the condensed matter physics theory group at Cavendish, had significant funding from Harwell, the British Atomic Energy Research Establishment in Oxfordshire, and surface science was the rage. In the petro-chemical industry (which was later to provide significant research funding to Pendry) new zeolite catalysts had just been developed for removing lead from gasoline, and understanding how atoms were arranged on crystalline surfaces was key. The success of surface science in the petrochemical industry spurred significant government investment in the field, and at Harwell and elsewhere, there was a strong push to better understand the theory, in the hope that even more breakthroughs would be forthcoming.

One of the key probing technologies recognized for characterizing surface atomic structure was low energy electron diffraction (LEED), developed by Clinton Davisson and Lester Germer at Bell Labs in the late 1920's [2]. Davisson shared the 1937 Nobel Prize in Physics with George Thomson, (son of Nobel Laureate J.J. Thomson), then at Imperial College London, for this discovery of electron diffraction. The LEED technique sends low energy (1–100 eV) electrons onto a highly

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[1]Imperial College London is situated in what I can only describe as the penultimate mix of urban and suburban living at the heart of a great city. Bordering Hyde Park and Kensington Gardens, but encompassing Royal Albert Hall, the Victoria and Albert Museum, the Museum of Science, and the gargantuan Natural History Museum, it is both a place for serious science and serious tourism. On a warm and sunny Friday morning this past August 30th, I met up with **Sir John Pendry** in his office on the 8th floor of the Blackett Physics Laboratory for the interview that comprises the text of this article. Following more than 3 hours of serious discussion, we took a leisurely lunch break during which Sir John revealed a few of his more juicy stories. However, the reader will have to be satisfied with the content that was amassed in the confines of the office. After all, we are dealing with the person who came up with the concept of the Metamaterial cloak of invisibility. Fortunately, I have no doubt that you will be sufficiently satisfied with those stories that do appear!

[2]"He (Pendry) is one of the few research students that I have had who did things independently that I could never have done myself [1]."

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ordered surface and measures the scatter pattern on a surrounding CRT screen. At first relatively underutilized, LEED was having a renaissance by the mid-1960s due to significant improvements in sample prep, the spread of ultra-high vacuum techniques, and a new detector technology that imparted a high velocity to backscattered electrons so they would show up easily on the surrounding phosphor screens. However unlike X-Ray diffraction, which relies on simple kinematics, LEED had severe interpretation problems because there were simply too many collisions along the surface before the electrons emerged, to effectively analyze with existing mathematical techniques.

At Heine's suggestion, Pendry plunged into electron diffraction theory in order to try and come up with a viable method for reconstructing surface atomic structure from LEED data. Pendry found a clever shortcut to the full 3-D scattering problem by focusing on the weak backscattered electrons. He derived a successive approximation approach that broke the problem up into 2-D atomic level slices along the surface, and then combined the exact piecewise solutions on the periodic sample using a perturbation approach. Pendry not only came up with the method, but coded it up on a computer and freely distributed the code to anyone who was interested in it. The technique was so successful it is essentially unchanged to present day. Pendry's first papers on this subject focused on a more accurate mathematical model for the pseudo-potential wave function and its application to describe electron diffraction [3]–[6]. Successful experiments were carried out with Volker Heine [7] and others [8], [9] that eventually led to the complete theory [10]–[12] with verification on a copper surface [13]. This analytic technique was a significant breakthrough, and not only earned Pendry his doctoral degree in 1969, but also a post-doctoral research fellowship at Cavendish. Pendry later teamed up with University of Gothenburg experimental physicist, Stig Andersson, to make the first ever measurements of surface cell atomic structure [14]–[16] based on his LEED analysis technique.

By 1971, Pendry was anxious to expand his research experiences. At Cavendish, Bell Laboratory researcher, Philip W. Anderson (1977 Nobel Prize in Physics), was leading the condensed matter physics group in which Volker Heine and Pendry worked as theorists. It was an extremely exciting time for condensed matter physics, and Bell Laboratories was certainly at the epicenter. Anderson was able to set up a post-doctoral appointment for Pendry at the Murray Hill lab in 1972. When Pendry arrived in New Jersey it was like being back at his family Sweet Shop. There were so many tempting projects to get involved in and so many creative people with which to work. In the short time he had, he focused on two tasks. First, he did some groundbreaking work with Patrick A. Lee (Dirac Medal winner, and now at MIT) on the interpretation of X-ray absorption fine structure (XAFS) data. Lee and Pendry attributed the fine structure to the excitation of core electrons and published a very widely cited paper [17] that allowed for the interpretation of localized atomic features particularly relevant for understanding chemical bonding. Second, and incredibly, Pendry found time at Bell to complete a very thick (400 pages), and later to become a classic text on the LEED technique [18]. In a rather unusual coincidence for the THz community, one of Pendry's nearby officemates, and acquaintances at Murray Hill, was fellow UK physicist Tom Phillips [19].

When Pendry returned to Cambridge in 1973, he was given a junior tenure track teaching appointment, while continuing to work on surface state physics at Cavendish. However, teaching was demanding a lot of his time, and he felt much more useful doing research. After almost 3 years on the teaching track, Pendry was frustrated with the low salary, slow creep up the academic ladder, and the bureaucratic accoutrements that accompanied lecturing. It was a godsend moment when Volker Heine walked into his office one morning in 1975 and asked Pendry who he thought might make a good candidate for a newly established post as head of theoretical physics at the Daresbury Nuclear Accelerator Facility in Cheshire. The UK Science Research Council (SRC) had decided that Daresbury was going to be equipped with a new synchrotron and the staff restructured to shift away from high energy research, and into condensed matter physics. Apparently the civil service position at Daresbury paid so poorly, that the SRC was having trouble finding a suitable candidate to take the job. Pendry sheepishly suggested that perhaps Heine might recommend him for the position. A few short months later, Pendry found himself Senior Principal Scientific Officer at Daresbury in charge of a large group of theoretical physicists.

Timing is everything in life, and Pendry's decision to leave Cambridge at the tender age of 32, trading a Professorship at one of the world's most prestigious institutions, for a low paid Research Management position, might seem a bit daft. However, Pendry looked at the management post as a desirable expansion of his professional skillset, a challenge to his self-assessed "geekiness" and a chance to build up and "call his own," a research team that focused on a field he was already heavily invested in. It was also a good time personally for Pendry to make the move back to northern England, as he had by this time met and married his wife of more than 35 years, Patricia Gard, who had been a post-doctoral student in mathematics at Cavendish (group theory) and even collaborated with John on one of his early papers [20]. As it turned out, shortly after his appointment at Daresbury, the Wilson Labour Government reversed its policy of freezing civil service salaries, and Pendry got a 30% raise!

At Daresbury, Pendry started to get interested in surface photoemission and began using his experience with X-ray absorption fine structure to work on a calculation approach for the much more complex valence band interactions that dominate this process. His theory for angle resolved photoemission [21], [22] gave unprecedented accuracy to the determination of the band structure of electrons on surfaces and in solids. He also developed a theory for "inverse" photoemission, from electrons that decay into unoccupied surface states [23], [24] which is widely used today. At the same time, Pendry continued to supervise students at the Cavendish, and in a series of papers with Steve Gurman [25], [26] and Pedro Miguel Echenique [27] (later to become a Basque University Professor), explored criteria for the existence and the nature of surface states. These could be probed with the photoemission techniques he had developed [28]. With Echenique [29]–[31], Pendry laid out a methodology and computational technique that set the criteria and led to experiments for resolving image—potential—induced electron surface states on metals—so-called "Rydberg"

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surface states, where the Coulomb tail on the electron potential forms a Rydberg series. These states result from trapped surface electrons with energy slightly below the vacuum level. The exploration and observation of image states has since become a common tool for understanding many-electron effects on surfaces.

During the period between 1975 and 1981, Pendry fulfilled the promises he had made when he accepted the position at Daresbury. He transitioned the theoretical physics group smoothly into condensed matter research, and was well prepared when the synchrotron finally came on line in 1981 [32]. At the same time, he worked on many different problems in surface science and published more than 60 papers, most of which are single authored. Those with more than 100 citations are listed in [33]–[37]. Pendry recalls these years at Daresbury very fondly, claiming that he learned a lot about managing people, as well as coming of age personably. He credits the particle physics staff with an exceptional generosity in accepting both himself, and the changes in direction he was bringing to Daresbury. He and his wife Pat, used their home to both house and entertain visitors and staff alike, and through this more intimate setting, encouraged a large network of close colleagues and friends.

By 1981, Pendry had reached the highest level civil service position at Daresbury that would still allow him to do research. With his transition of the nuclear physics group into condensed matter research complete, he began to look for other challenges. An opening as Professor of Theoretical Solid-State Physics at Imperial College was being advertised, and Pendry applied for the job. He moved to London later that year and changed his lifestyle from one of rural socialite and home owner, to that of commuting city dweller and apartment renter.

Just as when he had left for Daresbury, the economic situation in the U.K. was dire, and universities were suffering from severe cutbacks in resources. Pendry not only took a pay cut, but had to survive through an era when phone calls were limited to "low rate" times of the day in order to save on university overhead! He also felt the lack of structure and oversight in the university system, and was thrown into a battle for resources that seemed to have no one in the decision making role who cared about the outcome. The first several years were difficult, and Pendry turned to some of his old sponsors from the Cavendish years for support. The petrochemical industry (British Petroleum, in particular) was still very interested in surface science and potential commercial gains from LEED and XAFS. Pendry concentrated on scattering theory, introducing Tensor LEED [38]–[40], an accurate method for calculating the scattering signature of very complex surface structures that was not possible beforehand. Also, with the Erlangen group of Mueller and Heinz, he introduced Diffuse LEED [41]–[44], a method for analyzing electron scattering off randomly adsorbed atoms to allow a determination of their connection to surrounding atoms. XANES (X-ray absorption near edge structures) was also a favorite theme, with its multiple scattering events and photoelectron backscatter signature [45]–[48]. This technique was also applied to proteins [49].

Pendry was well supported for his surface science research on LEED, XAFS, and XANES, and decided he was going to take a chance and tackle a different problem in condensed matter physics that had particular interest for him. The problem had been formulated by his former group head at Cavendish, Phil Anderson, and was known *as Anderson localization*. The question was, what happened to electron propagation in a solid when the solid became distorted? Anderson had shown that there was a "snapping point" as the level of disorder crossed a threshold, when a resistive solid suddenly became an insulator. In the insulator state, the electrons could only propagate by tunneling, and therefore became *localized*. The mathematical explanation for this behavior was very subtle. Pendry spent about five years, between 1985 and 1990, trying to solve the general theory (which yet remains unresolved), but in the end managed to nicely lay out the case in one dimension [50]–[55]. A fundamental, and rather startling result of this work, was the prediction that as a complex solid with disordered scatterers grew thicker and thicker, with less and less energy reaching through the sample, there was still a statistically significant condition under which the electrons could all get through. In other words, electron transport channels through complex disordered systems, no matter how thick the material, could under certain conditions, be fully open (100% transmissive) [56]. Pendry called the finding the *Maximal Fluctuation theorem* [57]. In 1990, not too many people appreciated the discovery. However the *Maximal Fluctuation theorem* became extremely relevant when, 17 years later, in 2007, Allard Mosk at University of Twente, Netherlands demonstrated 1000 times increase in intensity of light transmission through an opaque scattering medium by controlling the incident wave front [58], [59].

Having completed his work on electron transport in disordered solids with little fanfare, Pendry decided to take up a different course of investigation. He had read the now classic paper by Eli Yablonovitch on the impact of a three dimensional periodic band gap structure on spontaneous emission in semiconductors [60] and the subsequent papers on engineered band gap structures [61]–[63]. He was very excited about the possibility of applying his electron transport analysis techniques to the world of photonics—which was now entering a real renaissance. Pendry began by developing the first computational techniques for calculating scattering of electromagnetic radiation in dispersive optical materials [64]–[66] and especially in metallic structures [67]. He then created computational codes that were very widely distributed in the scientific community [68]–[70]. His techniques, based on transfer matrices, enabled the calculation of the interaction of light with metallic bandgap structures with much higher precision than then current plane wave approaches.

Pendry delved into photonics with a passion and, between 1990 and 1999, produced many original ideas and highly cited papers, including transmission through narrow slit gratings [71], an explanation for surface enhanced Raman scattering via trapped light in closely spaced metallic spheres [72], refraction at very short length scales [73], optical [74] and spectral [75] properties of carbon nanotubes, infrared photonic band gap structures [76], and electromagnetic forces between nanostructures [77]. He also looked at friction due to van der Waals forces [78], [79] and the impact of near field coupling on thermal transport across a subwavelength gap [80].

In 1998, Pendry became head of the Physics department at Imperial College. He brought his management experience at

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Daresbury to the post, and relished the challenge of making the physics department a better place to work. As with his teaching post at Cambridge however, his time for research activities was to be significantly taxed. This did not stop him from coming up with new ideas, and the three years during which he served as department chair could arguably be considered the most fruitful in his long career.

Metamaterials

Pendry had been thinking about radar absorbers under an industry contract he had from Will Stewart, the chief scientist at Marconi (then part of General Electric, U.K.). Marconi was selling a group of carbon based absorbing materials for the microwave regime and was interested to know how they worked, in order to improve performance. The absorbing material consisted of long thin carbon fibers that, individually, were resonant scatterers over a narrow frequency range consistent with their length. However when they were grouped together the fibers acted as excellent broad band absorbers. Pendry realized that the individual fibers supported current, and when they were very close together ($\ll \lambda$) were inductively coupled via the induced magnetic field. He worked out the analytic formulation and very successfully compared it to the radar absorption data supplied by Marconi [81].

The inductively coupled resistive fiber problem stimulated Pendry to consider fully conducting structures of similar arrangement. The external RF field, in inducing current flow on the thin wires, constituted work, and the slowly accelerating charges along the wire could be treated analytically like heavy electrons. The combined structure, of the closely coupled metallic wires and the sparse electron flow, behaved like a plasma with a resonance that fell in the gigahertz regime. Below the resonance the structure was completely reflecting ($\varepsilon < 0$). Above the resonance, modes could readily propagate. Pendry had come up with an artificial plasmon structure for the radar region of the spectrum [82]. Colleagues at Imperial College subsequently fabricated some test structures made of gold plated tungsten wires which worked as predicted. Researchers now had a plasmon structure they could easily fabricate and experiment on using the wealth of available microwave instrumentation. Pendry thought about trying to develop a similarly acting structure composed of closely spaced metallic spheres (with reference to the enhanced surface Raman effect analyzed in [72]), but Marconi went belly-up before he got the chance.

The thin wire plasmon array acted on imposed RF energy through artificially enhanced electric permittivity that operated through magnetic field coupling. Pendry was curious about an equivalent structure that might use enhanced magnetic permeability to act through the electric fields in a similar manner. There were several radar materials that utilized embedded ferrites to enhance magnetic absorption, but they were generally very bulky and heavy, and were not able to achieve the high permeability that was analogous to high permittivity dielectrics. In a true Eureka moment he came up with the idea of using very closely spaced ($\ll \lambda$) metallic sheets configured in a Swiss roll pattern [83]. The tightly coupled cylindrical coils had very large self-capacitance, which allowed circular currents to flow when a magnetic field parallel to the cylinder axis was present. The structure had a natural resonance that could be tuned in the microwave region and an effective permeability that could be varied over a wide range. Pendry also realized that this structure, like the stacked wires, had a frequency regime, this time above the plasma resonance, where μ was negative. The first intended application was for picking up the magnetic fields in an MRI machine, hence the resonant frequency of the first Swiss role was close to 20 MHz (Pendry showed me a hand sized sample in his office). The Swiss role is not ideal in that its behavior is strongly anisotropic, never-the-less this early structure, as well as the two thin wire constructs that Pendry had already analyzed [81], [82], were in fact the first realized *metamaterials*.[3]

With the concept of engineered materials having tailored electric and magnetic properties firmly on the *radar* screen, Pendry, in another Eureka moment, subsequently came up with an isotropically configurable design for a *planar* magnetic circuit element that would become the basis for a whole class of future 2-D and 3-D metamaterial structures — the split-ring resonator [83].[4] Using a pair of interleaved closely spaced subwavelength conductive loops, each containing a small gap in the ring, allowed Pendry to form a resonator element with a tailored inductive and capacitive ladder network equivalent circuit. Varying the loop length, wire width and gap spacing allowed him to create a resonance at any desired frequency from GHz to THz. When the individual loops were arranged in a subwavelength spaced periodic lattice (2-D and 3-D cubic arrangements were envisioned and analyzed), the bulk magnetic permeability could be adjusted, positively or negatively. The permeability could also be enhanced to create materials with extremely high magnetic field (with an effect analogous to surface enhanced Raman [72]).

Pendry presented both his tailored electric permittivity and magnetic permeability structures at a sold out workshop on artificial photonic bang-gap (PBG) structures organized by PBG pioneer Eli Yablonovitch (then at UCLA, now at UC Berkeley) and others, in Laguna Beach, California in January 1999.[5] Several papers from the workshop were published in the November 1999 issue of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES including Pendry's [83], which is now his second most referenced paper on Web of Science, with over 3200 citations. It was at this conference that Pendry met UC San Diego Professor Sheldon Schultz and David R. Smith (now

[3]The term "metamaterial" is attributed to University of Texas at Austin Professor, Rodger M. Walser, who opened a special invited session with this title at the American Physical Society meeting in Minneapolis, MN, USA, on March 24, 2000 [84], and who credits this talk with the suggested terminology to "recognize that their *(metamaterial)* architecture is aimed at achieving performance beyond that of conventional macroscopic composites"[85]. See, also footnote 4.

[4]Note that the split ring resonator as well as the stacked thin wire array were both concepts that had some historic precedence. The split-ring was analyzed in Schelkunoff and Friis's classic text, *Antennas: Theory and Practice* (Wiley, 1952), and the wires in Rotman's classic paper, "Plasma simulation by artificial dielectrics and parallel-plate media," in the IRE TRANSACTIONS ON ANTENNAS AND PROPAGATION, vol. AP-10, no. 1, pp. 83–95, Jan 1962. Pendry was unaware of these papers at the time, and his structures differ somewhat from these classic examples as well.

[5]Workshop on Electromagnetic Crystal Structures, Design, Synthesis, and Applications (PECS-I), Eli Yablonovitch, Axel Scherer, John Joannopoulos, Thomas Krauss, Toshihiko Baba and Jonathan Dowling organizers, Laguna Beach, CA, Jan. 6-8, 1999.

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at Duke University), as well as many other pioneering metamaterial researchers.

Schultz and his group at UC San Diego had been working on engineered structures like Pendry's [86] and realized that they might have some very practical applications. The two groups agreed to share information and to try fabricating some structures that included Pendry's split ring resonator. What happened next can only be expressed as an *historic breakthrough*. Schultz's group produced a structure that combined close packed wires with the split-ring resonator to realize an artificial material with both *negative permittivity* and *negative permeability*[87]. Immediately after seeing the result, Pendry realized that the San Diego team had constructed a material with *negative* refractive index [88]. It was the start, in Pendry's words, "of a firestorm, both of positive activity (that has since launched many careers), and extraordinarily acrimonious responses," to an exciting new way of looking at an electronic material construct.

Shortly after hearing about the UC San Diego result, Pendry began thinking about the implications of having a configurable material with a negative index. He was aware of an early paper by Russian physicist V.G. Veselago that had predicted some properties of a material formed of negative ε and negative μ [89]. He was mulling over some ideas at home one weekend and wondering if the resulting *negative refraction*[6] from the negative index would follow the Abbe diffraction limit in the same way as a positive lens. That is, would a "negative lens" have a resolution limit that was limited by the wavelength? He went back to Maxwell's equations and started fiddling with the field solutions in the presence of a negative index. What he found was surprising: when the index was -1, the lens could be "*perfect*" with no limit on the resolution. Essentially the negative index allowed one to capture both the propagating electromagnetic fields, and the evanescent waves, to recreate a perfect image, without restrictions due to diffraction. He showed his conclusions to his wife Pat and remarked that, "if he published this result it would either make him famous or infamous." She told him to put his work away and have lunch!

Pendry put the calculations aside and did not go back to them for some weeks. He finally decided to show the result to some of his optics colleagues at Imperial College, Martin McCall and others. They could not find anything wrong with Pendry's mathematics, but thought it was going to be a very controversial conclusion to publish. Indeed it was. Pendry had a very rough time getting the article accepted by *Physics Review Letters*. Eventually it did come out in October 2000 [90], and the resulting firestorm was even worse than that over negative index. Pendry was so busy with his department head functions he had little time to argue with every critic individually, so he let the controversy rage around him, confident that so long as his mathematics were sound, his conclusions would have to be accepted, eventually.

It took several years, but the "*superlens*" concept has not only been accepted theoretically, but has been demonstrated both in the microwave regime, in a wonderful experiment by George Eleftheriades and Anthony Grbic at University of Toronto [91] in 2004, and a year later in the optical regime, by Xiang Zhang and colleagues at UC Berkeley [92]. It is an exceedingly wide impact, and now practical application of the mathematical properties of metamaterials, a goal that many good theorists, and Pendry in particular, strive for. Not surprisingly, the perfect lens paper [90] is Pendry's most widely referenced publication with almost 5000 citations.

In 2001, Pendry left the post as department head at Imperial, but continued to focus on the negative refractive lenses as well as other photonic bandgap and metamaterial constructs and applications. He had particularly strong collaborations with post-doctorate S. Anantha Ramakrishna (now a professor at Indian Institute of Technology, Kanpur, India), and with David Smith, who is now at Duke. Of Pendry's more than 40 papers between 2000 and 2005, one-half have had more than 100 citations [93]–[114]. In particular, his theory paper with Martin-Moreno *et al.* [94] on optical transmission through subwavelength holes in metal films, spawned a whole field of development on subwavelength apertures and plasmonic structures in the microwave-through-THz regimes (see, for example, papers by Stefan Maier at Bath University [115]). For his extraordinary body of scientific achievements, Pendry was awarded the rank of Knight Bachelor in 2004, although he modestly kept his new honorific quiet in scientific circles.

In 2005, Valerie Browning, then a DARPA (U.S. Defense Advanced Research Projects Agency) program manager, invited Pendry to a closed meeting in San Antonio, TX, USA where he was asked to present a general talk on metamaterials. Browning particularly asked Pendry to challenge the audience. This he did, by finishing his lecture with a formula for manipulating the optical lines of force in such a way that one could produce an *invisibility cloak*. When he sat down he was amazed that no one was laughing. In fact the audience was very excited, and Pendry subsequently received a DARPA contract to further develop the concept. The word also got back to David Smith at Duke, who, like in the days following the Laguna conference in 1995, asked Pendry about the possibility of engineering and constructing a microwave version of the metamaterial structure. The two *Science* papers that appeared a year later, one on theory [116], and the other the demonstrated construct [117] for the *invisibility cloak*, again created a maelstrom of excitement and subsequent research activity. This time however, success meant a TV appearance and not just a scientific publication! Unlike the perfect lens, the cloak of invisibility was immediately accepted both by the science community and the general public.

Pendry continues to work productively on his plasmonic constructions and applications — which are now burgeoning into the new field of *transformation optics*. He has published 70 additional papers since 2006 and 16 in 2012 alone. Some of the most highly cited of these are listed in [118]–[139]. Many more are yet to come. For demonstrating his concepts, the length scales and fabrication capabilities in the Terahertz regime come together nicely, and more and more of Pendry's ideas are gaining popularity in this frequency range, as evidenced in the articles which follow in this Special Issue.

Above all, and despite his extraordinary skills as a theorist, Pendry is still true to his character as an experimentalist and to his days in the basement of his parents Sweet Shop, where ideas were translated into practice. "Unless you can get your idea into something you can make a product out of, your contributions

[6]Note that the negative index causes the rays entering the material to bend away from, rather than towards, the normal to the surface.

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will soon be forgotten." We spent the next half hour talking about all the Pendry ideas that are now being implemented into devices, ranging from satellite communications to biomedical instrumentation. *I am certain Pendry's ideas will not soon be forgotten*.

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John Pendry is a condensed matter theorist. He has worked at the Blackett Laboratory, Imperial College, London, U.K., since 1981. He began his career in 1962 as a student in Downing College, University of Cambridge, U.K., followed by graduate and post-graduate work in the Cavendish Laboratory, Cambridge. He then led the Theoretical Physics group at Daresbury Laboratory for six years until his move to Imperial College. Pendry has worked extensively on electronic and structural properties of surfaces, developing the theory of low energy diffraction and of electronic surface states. Another interest is transport in disordered systems where he produced a complete theory of the statistics of transport in one dimensional systems. In 1992, he turned his attention to photonic materials and developed some of the first computer codes capable of handling these novel materials. This interest led to his present research which concerns the remarkable electromagnetic properties of 'metamaterials' whose properties owe more to their micro-structure than to the constituent materials. These made accessible completely novel materials with properties not found in nature. Successively, metamaterials with negative electrical permittivity, then with negative magnetic permeability were designed and constructed. These designs were subsequently the basis for the first material with a negative refractive index, a property predicted 40 years ago by a Russian scientist, but unrealized because of the absence of suitable materials. Pendry went on to explore the surface excitations of the new negative materials and showed that these were part of the surface plasmon excitations familiar in metals. This project culminated in the proposal for a 'perfect lens' whose resolution is unlimited by wavelength. More recently, in collaboration with a team of scientists at Duke University, he has developed the concept of 'transformation optics' which prescribes how electromagnetic lines of force can be manipulated at will. This enabled a proposed recipe for a cloak that can hide an arbitrary object from electromagnetic fields. Metamaterials give the possibility of building such a cloak and a version of this design working at radar frequencies and exploiting the properties of metamaterials has now been implemented experimentally by the Duke team. Optical versions of the cloak have now been constructed.

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Sir John Pendry has also taken on many administrative roles and considers such skills essential for making wider contributions to science. He has been Dean of the Royal College of Science (1993–1996), Head of Department at Imperial College (1998–2001), and subsequently Principal of the Faculty of Physical Sciences (2001–2002). He has taken on the chairmanship of the Physics Sub-Panel of the 2008 U.K. Research Assessment Exercise, a huge task which he began in 2005. Elected a Fellow of the Royal Society in 1984, he has been Member of Council from 1992 to 1994, and Editor of the *Royal Society Proceedings A* from 1996 to 2002. For the Institute of Physics, since 2007, he has been Member of Council, Chairman of Institute of Physics Publishing and Vice-President and President for Publishing. He has received multiple honors and awards, recognizing his many scientific contributions including the Dirac Medal from the Institute of Physics in 2005, the European Union Descartes prize in 2005, and culminating in his knighthood for services to science in 2004. More recently, he received the Royal Medal of the Royal Society in 2006, a Fellowship at the American Academy of Arts and Sciences in 2012 and the 2013 APS McGroddy Prize—joint with David Smith and Costas Soukoulis. He also holds honorary degrees from Duke University, USA, Hong Kong Baptist University, and University of Erlangen, Germany, and is a Foreign Associate of the National Academy of Sciences.

Beyond science, Pendry has a love of music and is a fine pianist. He also enjoys gardening, photography, the countryside, and natural history: hobbies shared with his wife of more than 35 years, Patricia Gard Pendry.

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