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COMMUNITY PERSPECTIVE

Pioneers in metamaterials: John Pendry and Victor Veselago

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Abstract
This article is a tribute designed to praise two great scientists who have set the world alight by stimulating boundless curiosity about metamaterials. It is stated early on that it is not intended to be a technical review but one from which it is possible to understand what the excitement is about. To achieve this outcome some simple discussions of refractive index are used as a means of getting to the now famous concept of negative index. After some selective, quasi-historical, development, the article moves on to a specific section about the pioneers themselves. It presents some impressions of their backgrounds, including the fact that John Pendry is now known now as Sir John Pendry. This flows from the recognition of his work by Queen Elizabeth. It is acknowledged that Victor Veselago truly guided the world along the track of negative refraction with a remarkable display of prescience. It is asserted that metamaterials have a brilliant future and that very important work is progressing towards the production of loss-free and active negative index and other forms of metamaterials. It pointed out that the control of light paths through the distortion of space is currently a major outcome from the groundbreaking work of the pioneers and that, in fact, light concentrators and optical black holes may well be life-transforming consequences. Indeed, in the conclusion, it is stated, unreservedly, that the whole world is indebted to John Pendry and Victor Veselago.

Keywords: metamaterials, negative refraction, cloaking, pioneers

1. Introduction

This article is designed to praise two very important people, who have stimulated so much activity in the fascinating area of metamaterials. It is not to be a technical review but something that is more widely accessible. It contains just enough information, however, to enable a comfortable impression to be constructed of what precisely these two great scientists have done for the world, in terms of creating a lot of excitement and focused action. The wonderful modern poet Mary Oliver [1], in her poem 'What I have learned so far', asks us to recognize that 'All summations have a beginning, all effect has a story, all kindness begins with the sown seed. Thought buds towards radiance. Be ignited, or be gone'. In a very potent way, metamaterials ignited the world at the beginning of the last decade, and the flame was fanned by the idea of embracing negative refractive index materials, some aspects of which will be outlined below. The ignition point occurred at a much earlier time than the last decade, however, through the seminal negative index work of Victor Veselago [2]. To this has been added the groundbreaking work of John Pendry [3] that magnificently stoked the fires of both curiosity- and application-driven search for negative refractive index media at the turn of the new millennium. The world truly became ignited and enthused by the pivotal experimental observation of this type of refraction [4].

In order to access the early concepts emanating from the work of Pendry and Veselago some elementary points will now be made. The first everyday observation is that substances, in various forms, refract at optical frequencies. This is well-known to everybody, without having to be a scientist. Indeed, it is not necessary to embrace optics as a discipline to appreciate that lenses seem to work as they are expected to, and that rainbows can appear in the sky [5]. The common view would

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John Pendry

Victor Veselago

be that this is all about the magnitude of something called the refractive index, which is the measure of how much light slows down when passing from a medium like air into glass, for example. It is customary to set the sign of this index to be positive and associate it with transparent materials. The use of an index to divide into the speed of light in an unbounded material to get a smaller value than it has in a vacuum lies at the heart of the familiar Snell's law, which preceded the publication of Maxwell's equations by over 200 years. The idea of attributing a negative refractive index to materials like glass, or water droplets in the sky, seems to be unnecessary and, indeed, perverse. Assigning a positive value is enough and is apparent common sense. This argument holds up nicely, without the use of Maxwell's equations, when it is believed that optical magnetism is not a feature of what is being examined, when referring to ordinary, isotropic, glass windows, or rainbows. However, it can be guessed, quite reasonably, that if such materials did naturally, or unnaturally, possess both dielectric and magnetic properties then it may be necessary to think again about the sign of the refractive index. The main thought would be that maybe it is possible to discover, or manufacture, isotropic materials with a negative index, if only the scientific community could be sufficiently imaginative. A starting point is to deconstruct the meaning of the refractive index of a material and recognize that this is a derived concept that was being used in science long before Maxwell's equations appeared on the scene. Even after their arrival, refractive index did not emerge naturally from them. In fact, the refractive index is the square root of the product of the relative dielectric permittivity and the relative magnetic permeability of a material. This raises two interesting points. First, in taking a square root, mathematically, it has to be admitted that two signs are always on offer but, when dealing with apparently ordinary materials, taking the positive sign is a natural, and apparently obvious, choice. Secondly, it can be imagined that both the dielectric permittivity and the magnetic permeability could be negative, if only such a material could be found. If that is the case, then, perhaps, the conclusion is that such a double negative isotropic medium is best described by a negative index. These basic aspects developed into a vigorous discussion and it soon became clear that the history of negative refraction goes back a long way [6], if uniaxial (anisotropic) materials like calcite are used, for example. However, the real point is this. Nobody took any notice, until the last decade started to unfold, awakened the world and caused it to ask some really penetrating questions about what it felt it already knew so well. All of these comments paint a picture of an important feature of the scenario created by the Pendry–Veselago revolution that swept all before it with the tide of breathtaking metamaterial research in the last decade.

But, why introduce the word metamaterial? This is another aspect of the story of the Pendry–Veselago revolutionary decade, and the invention of the word is attributed to Walser [7], who celebrated the new millennium by introducing the name metamaterials for a description of the effective behaviour of composites, about which a little more will be said later. In spite of this attractive terminology for a new range of composites, the highly visible driver of global news and excitement, as stated earlier, actually was the wonderful idea of negative refraction in isotropic materials. Nevertheless, underpinning this excitement was, indeed, the need for composites, or metamaterials, in this area to act as demonstrators [3, 4]. This became more and more urgent and inspirational, not only to scientists but to the media as well.

Regardless of how many tracks can be made back into the early part of the last century, the world accepts proudly that the ignition point was the pioneering 1968 paper [2] by Veselago on the electrodynamics of isotropic substances with simultaneously negative values of dielectric constant and magnetic permeability. Within this beautiful work, Veselago categorically stated that there had not been, so far, any experiment in which a substance such as this could even be identified. He went on to discuss how to look for such materials, the impact upon the Doppler effect and the creation of special lenses based upon negative refraction. These wonderful ideas remained quietly in the background until the new millennium fanned the flames with the inspirational pioneering work of Pendry [8, 9] and ushered in the amazing ideas that underpin the development of these new materials, called metamaterials, capable of performing in just the way that Veselago imagined.

The new material science paradigm needed is described by the word metamaterial because it is like the word metamorphosis, which denotes a change of condition, using the Greek word meta that translates as 'after'. The central concept is to construct new materials from artificial objects, which can be called metaparticles. Such materials are composites that are not just the sum of their parts and therefore go completely beyond conventional ones. The task can be summed up in a deceptively simple way: it is necessary to create 'artificial molecules', i.e. metaparticles, to build such materials, if the kind of miraculous performances implied, for example, by isotropic negative index materials are to be harvested. This is actually quite a tough job, however, but if we can imagine creating suitable metaparticles and then assembling them into artificial composites, they should in principle produce a negative index medium, with the beautiful properties that Veselago suggested. Of course, recognizable outcomes, like a negative index, will all depend upon how the final composite material is interrogated. It will be necessary to use an electromagnetic wavelength that is much larger than the size of the individual metaparticles, for instance. If these metaparticles are arranged on a pane of glass, for example, the wavelength of our interrogating radiation must behave like an elephant in a flower garden and it will be only the average (effective) permittivity and permeability that will be sensed by its large footprints. The intriguing question is what kind of metaparticle can be made to get even close to the Veselago dream material?

Enter John Pendry [3], at the beginning of the millennium! He and his colleagues created wonderful metaparticles consisting of wires and split-metallic rings. The former yields a negative permittivity. This is expected because a metal, like the coins in our pocket, is like a box full of free electrons, moving against a neutralizing positively charged background lattice. In other words, it is a solid-state plasma, associated with quanta called plasmons. Also, metals are highly reflecting, so it looks as if the effective index is imaginary and that, because of the square root discussion given earlier, the effective relative permittivity for a metal is negative in normally accessible optical windows. This is a correct conclusion because at very high optical frequencies the electrons will behave collectively and the whole set of electrons in a metal can be shaken like a jelly. The frequency of this oscillation is naturally called the plasma, or plasmon, frequency [10] and this is very high, beyond the familiar visible frequency window. The net result at lower electromagnetic frequencies, even in the optical range, is that the electrons will oppose transmission by creating an imaginary index and there will be an effective negative relative permittivity. This is often called plasmon behaviour. On the other hand, a metal ring with a piece cut out of it (a split-ring) has a classical response to an incoming electromagnetic wave like a typical inductance–capacitance–resistance resonant circuit that can, in principle, scale up to high frequencies if plasmonic influences are taken on board as well. Faraday's law determines the induced electromagnetic force and Gauss's law the magnetic flux. A magnetic moment is now the outcome and hence a frequency-dependent relative permeability will assert itself. If the rings were alone the wave would be reflected for quite a wide frequency window so, once again, the effective index would be imaginary but this time there is an effective negative relative permeability in play. Clearly, combining these two negative properties using a metaparticle consisting of a wire and split-ring appears to be a highly desirable pathway to a negative index metamaterial.

In the year 1999 the pioneering work of Pendry and Veselago ushered in the era of metamaterials, focused upon the eye-catching negative index world that it opened up to so many people. Of course, much debate followed. Some of it was in favour and some of it was (not to make a joke of it) rather negative. But why did so much excitement ensue? It was the critical combination of seeking the double negative material property behaviour and the interface that Pendry created with the world of science and other disciplines. More specifically, this double negative search revealed something that was unfamiliar to the physics world and this was that, in an isotropic material, the group velocity and the phase velocity would have to travel in opposite directions to preserve causality. This was brought out quite clearly in the Veselago paper and, somewhat unfortunately, led to the bulk waves in a negative index medium being called left-handed because the phase and Poynting vectors are oppositely directed. It is not the case, however, that the medium has left-handed properties, and if you are an engineer you may not be so surprised because what is happening is the creation of backward waves [11]. They can occur in photonic crystals too.

The previous decade is now, somewhat whimsically, called the 'noughties', and it teaches us that new ideas in science often break with tradition and are visibly exciting enough to offer scope for change in many areas of life. This philosophy must be pursued in spite of objections, in spite of concerns about losses, or how to make the material in three-dimensions, and so on. Without going into detail, at the beginning of the last decade there were substantial doubts about the way a metamaterial community based around the negative index ideas would develop. In fact, it brings to mind a quotation from the famous Oliver Heaviside [12] who, incidentally, was the person really responsible for the vector creation of Maxwell's equations, as we know them today. Heaviside was being openly criticized for using his operator analysis before the mathematical world got around to showing that it was patently all right to do so. Heaviside simply retorted 'Why should

I refuse a good dinner simply because I do not understand the digestive processes involved?' The metamaterials area is exactly like having a good dinner, in the Heaviside sense, because there are still things that need to be sorted out and understood. They will be, and the world of science will stand indebted, for ever, to Pendry and Veselago. It is now an appropriate point in the article to give some more personal details of their profiles.

2. About the pioneers

Victor Veselago [2, 13–16] was the 2009 recipient of the C E K Mees medal awarded by the Optical Society of America (OSA) for interdisciplinary and international contributions to optics. The citation goes on to mention his invention of negative refraction (sic) which spawned widespread international activity in the multidisciplinary field of metamaterials. Victor, of course, is a well-known and well-recognized figure throughout the world and he is a global expert on the physics of magnetic materials, photo-magnetic phenomena and the propagation of electromagnetic waves in solid-state plasmas. He is the head of the Magnetic Materials Laboratory at the famous A M Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow. In his astonishing 1968 paper, after considering the simultaneous negative values of permittivity and permeability, and its impact on such things as the Doppler and Cerenkov effects, he made some seminal suggestions about special lenses that could have parallel plane sides: now called Veselago lenses. Veselago received both his PhD and his DSc in solid-state physics from the Lebedev Institute and, in addition to being an OSA medal winner, he is a Russian Federation winner of the State Prize in Science and is also the winner of the V A Fock Prize. Among his other duties he lists being a member of the Advisory Boards of the journals *Metamaterials* and *Optics Communications*. It can be truly acknowledged that he guided the world along the track of negative refraction and that his work has proved to be remarkably prescient.

It was for services to science that John Pendry was honoured by Queen Elizabeth and became a Knight of the Realm. He is now entitled to call himself the honorific Sir John, without using the family name. Sir John has made many contributions to science but his work in metamaterials alone would be worthy of a knighthood. He received both his MA and his PhD from the University of Cambridge and is Professor of Theoretical Solid-State Physics at Imperial College, London and became a Fellow of the Royal Society in 1984. He received the European Union Descartes Prize for 'extending electromagnetism through novel artificial materials', the Royal Medal in 2006, the Institute of Physics Dirac Medal and prize in 1996, and a number of other prizes in other areas and public recognition through invited pivotal lectures that have entertained and stimulated people throughout the world. Sir John was the first to recognize how important the farsighted paper of Veselago really was and his work on low-frequency platforms in thin wire structures provided a huge stimulus [3, 17]. His beautiful investigations released an activity throughout the world that is very difficult to surpass, in any field. It has led to tremendous efforts to find out if negative refraction can really be created and his work stimulated the imaginative work of the group led by Smith [4], who demonstrated the kind of negative refraction that has been talked about above.

The pathways opened up by the pioneers John Pendry and Victor Veselago show that the ignition point created by Victor could indeed be fanned into flames in the sense that Mary Oliver [1] talks about in her poem. Sir John made many tremendous luminal strides, providing thresholds of opportunity for many research groups around the world. Not least among these opportunities was the explanation and development of the idea of special lenses [8] that was introduced by Veselago [2]. Sir John added so much insight into how they could actually work. He put them truly on the map again and the Veselago lens is now referred to as the perfect lens. This is because small details (actually sub-wavelength features) of the original object are often lost in near-field imaging due to the exponential decay of some vital Fourier components. Sir John clearly showed how the use of a negative index material could lead to amplification and the ability to regain the features that are normally lost. This could be vital to imaging of deleterious processes with keyhole medical techniques.

Very brilliantly, Sir John has also suggested the possibility of cloaking [18] that involves trying to divert the path of light to make something invisible, or cloaked. It is so exciting that the technique involves transformation optics and ideas that go back to general relativity [19–21]. Furthermore, the diversion of light in this way does not require double negative media. The special issue following this tribute to Pendry and Veselago will highlight many new ideas in this area.

3. Metamaterials: a brilliant future

In all of the above, the negative index discussion is used to bring out how the field got under way and the principal intention is to recognize two people for their very special achievements, within the area of metamaterials, which this journal treats as a special area of attention. The world stands in awe as it witnesses their endless curiosity, their huge capacity for work, their willingness to defy convention and how their work happily started off a decade of excitement in metamaterials. These scientists are heroes and the excitement is not over yet: not by any means. Even though this brief article is not meant to be a review of metamaterials, it does indicate some delectable points of contact that excite immediate scientific and public interest. It is fitting, therefore, to approach the end of the article by giving a brief discussion of where the subject is heading, implicitly giving thanks for the new ways of thinking that have been stimulated, throughout our community, by the pioneers John and Victor.

In a developing subject like this, restricting attention just to, so-called, double negative media is far too restrictive and, today, a more general family of metamaterials is being investigated, and designed, of which a simultaneously negative permittivity and permeability metamaterial is just one of the members. All the work is so full of promise that there are bound to be both real, and perceived, difficulties. Not least among these is the creation of the necessary materials. One of the difficulties could be associated with excessive losses [22, 23]. These come naturally with the resonant behaviour of the sub-wavelength, metaparticle, constituents of metamaterials. The good news is that the latest solution from Vlad Shalaev and his team offers loss-free and active optical negative index metamaterials [24]. Hence loss is not likely to be a major problem, for much longer, when the final material designs are created. The remark made by Heaviside applies just as much today as it did in his time.

Work is progressing on both super-lenses and hyper-lenses [25, 26], or whatever they are finally going to called, whether for near-field or far-field applications. There is wonderful work going on to operate confidently in the optical domain by Shalaev [27, 28] and his group, to name just one area of activity. This could well be important for optical computing and the stopping of light in the sense discussed under the heading of trapped rainbows [29]. Given that part of the metamaterial community is racing towards the optical frequency range, it is appropriate to ask if the construction of such metamaterials can create a significant social impact. It is already the case that Schwartz-Getzug [30] has reported how the safety of the lives of women collecting firewood in Chad has been dramatically changed through the introduction of solar cooking. This has been done using metal foil on cardboard as reflectors but it should be possible to create special panels that are able to absorb light, without reflection or transmission, from any direction. These could be used as heat sources and could be achieved by using metamaterial coatings or layers [31, 32], and work is progressing on this. The impact around the world will be immense. Metamaterial design is a work in progress and beautiful ideas keep emerging that enhance and open up new pathways, such as optical activity without chirality [33].

If we step back from the optical range of frequencies and consider a frequency window squeezed between the infra-red and the millimetre range, covering the low THz to just beyond the 10^{13} Hz scale, it can be appreciated that this is a rather important frequency range for medical applications [34]. Natural materials in this area are difficult, or impossible, to locate and the consequence of this limitation is the small number of devices available for medical work. Metamaterials, when they are fully developed, will fill this gap so that nondestructive THz imaging can evolve and assert its superiority over the use of ultrasound, or x-rays. Indeed, the use of THz technology will transform the analysis of breast and skin cancer and also osteoarthritis research. The key point is that the advent of metamaterials into the THz gap will give us the ability to distinguish between biological tissues, good or bad, and add so much to the quality of life when put into practice as corrective surgery [35].

On cloaking, or invisibility, it is safe to say that the world will continue to be fascinated by this idea. Within controlled environments the idea of being able to hide things and make light travel around objects is so exciting that in the beginning it really did not matter what the applications were going to be. Nevertheless, the bending of light paths, and the distortion of space, is such a compelling possibility that many more realistic possibilities will flow out into the world [36]. It is also being suggested that we can bear off in another direction because, as Vlad Shalaev quite rightly says, ‘one can not only exclude light from some region, but one can also do the opposite and concentrate light within a certain area’ [27]. In fact, it is possible to formulate optical attractors, with transformation optics designs, or other techniques, that can be referred to as optical black holes [37]. In addition, the whole question of nonlinearity [36, 38, 39] is now also being intensely addressed globally with a variety of techniques [40]. This research direction will introduce tunability and the possibility of exotic soliton behaviour. Finally, moving to spacetime, cloaking is the latest fascinating development to flow from all of these ideas and leads us into the exciting possibility of hiding complete events, as well as objects, an outcome that is being labelled as a history editor [41].

4. Concluding remarks

This is a tribute to the far-reaching imaginations of the two pioneers, John Pendry and Victor Veselago. As the century progresses, later generations will appreciate how their daily life, their health, their entertainment, and their research directions, owe so much to metamaterials. Even from the brief outlines given above, it can be seen that the possibilities are endless. They will continue to be very important from a scientific curiosity point of view, and they will have a very strong impact on all aspects of our life. To realize that all of this flows from the seminal work of the two heroic pioneers being celebrated here is staggering and brings to mind a final quotation, concerning a meeting of the great scientist Michael Faraday with William Gladstone, who was later to become Prime Minister of Great Britain. Gladstone asked Faraday what was the actual real value in practical terms, or even the point, of studying electricity. The reply from Faraday [42] was ‘there is every possibility, sir, that, one-day, you will be able to tax it’. This comment sums up the desire of all scientists not to have their curiosity diminished by too much emphasis on practical applications because, indeed, the latter will inevitably come, often in a very direct form. The life that the study of metamaterials has breathed into the last decade of science has been curiosity-driven but, as Faraday was hinting at, many benefits will flow from it. Above all, however, the world is indebted to John Pendry and Victor Veselago.

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