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The futures of transformations and metamaterials

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Abstract

Those researchers who are part of the metamaterials community stand at a fork in the road – does the maturation of metamaterial fabrication lead to a focus on applications and technology, or does it suggest an opportunity to pursue more blue-sky scientific concepts? At Metamaterials 2013 in Bordeuax, one speaker focussed explicitly on the opportunities for applications and funding on the road leading to metamaterial technology. Here, in deliberate contrast, we look instead at the interesting opportunities in curiosity-led research based around the ideas of transformation and metamaterials. The genesis of this article was the Transforming Transformation Optics meeting held at Imperial College London in December 2013.

Keywords: Discussion; Futures; Metamaterials; Transformation

1. Introduction

The discussions in this article were prompted by two events – first, the successful session at Meta 13 in Bordeaux with the same "future" theme, and, second, by the self-imposed task of running an alternate futures discussion session [1] at the "Transforming Transformation Optics" one-day meeting organized by us in 17th December 2013 (Fig. 1).

As theorists, although the points covered and discussed in Bordeaux were interesting and relevant, the very specific focus on converting transformation concepts and metamaterial ideas rather directly into applications and technology seemed somewhat limiting. Surely transformation-based theories such as transformation optics or transformation acoustics are not completely played out as far as conceptual advance goes? Indeed one of our primary interests is to merge many or all types of such theories into a unified "transformation media" theory – at least to the extent to which it is possible [2,3]. Notably, we can at least understand the design specification – the "Transformation Design" (T-Design) – of a transformation device (T-device) such as a cloak independently of the physical implementation in T-Optics (i.e. in electromagnetism, EM) or in T-Acoustics (i.e. in acoustics).

Of course, as co-creators of the concept of spacetime transformation design [3–5], we may be predisposed to a particular view, but perhaps surprisingly, the spacetime transformation concept has had rather minimal attention from other workers so far. This is despite three rather nice nonlinear optics experiments [6–8] but the concept is scarcely overdue for being subsumed into engineering. That said, as the Cornell experiment showed [6], pre-existing time lens devices based on dispersion are ideal for implementing spacetime T-devices.

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Fig. 1. Participants at the December 2013 meeting *Transforming Transformation Optics*.

Here, as a deliberate counterpoint to a current emphasis on applications, we discuss a range of other new alternative concepts that will typically need further research investigation before they develop into the status of applications. Of course the target audience of this journal *would* probably be most interested in those applications and experimental systems; and the summary of "obvious futures" in Section 2 would therefore seem most relevant. However, it is important to keep an open eye on other developments, either potential or in-progress, because of the opportunities they present. Perhaps considering the limitations of the "coordinate transformation" view of T-Optics, as discussed in Section 3, will provide a clearer intuition; or taking a bird's eye, more abstract view of transformations (Section 7) may serve the same purpose. Would you have expected nonlinear optics to be the first research field that experimentally demonstrated the T-Optics spacetime cloak? (Section 4). What other kinds of geodesic or conformal T-devices might be mooted following the summary in Section 5? – consider the strong current interest in surface wave and other 2D devices. What thought-provoking systems might we make with hyperbolic systems (Section 6) while intending to mimic spacetime like behaviour in a purely spatial system? Can we really turn such ideas into realistic metamaterial constructs without the necessary design compromises confusing the essential idea? These are important questions, and it is only when the more experimental side of the T-Optics research community come to grips with the theoretical proposals, will we know the answers.

2. Obvious futures

One might explore some of the more obvious future directions for metamaterial and transformation work simply by first selecting a recent review article [9]. We can then envisage improving the devices therein – making them work in the visible spectrum, improving the bandwidth covered, designing smaller, better, or otherwise enhanced – perhaps even chiral [10] – meta-atoms. Theoretical schemes for numerical simulation [11,12] or for homogenization [13–16] might be improved, either by increment or step advances. More investigation could be done of multifunction "Janus" devices [17], the transformation of fields, boundaries, and impedances [18–22], Poynting vectors [23], or sources [24]. Reimagining T-Optics as a generalization of Snell's Law [25] also shows the way to provide updated intuition, as does improvement in publicity and outreach efforts [26].

Another straightforward future concept centres around the potential for nonlinearity in T-Design. If using standard T-Design techniques, nonlinearity is hard to handle in all but rather abstract ways [27]. Nevertheless, it can be put to service rather more simply as a way of controlling standard T-devices by utilizing the nonlinearity as a switching or modulation mechanism – e.g. the optical fibre scheme based on speed control by means of nonlinear refractive index, as originally proposed for the spacetime cloak [4]. Of course, the issue of EM propagation techniques in metamaterials has been addressed in a substantive way – if finite difference time domain (FDTD) methods [28,29] are too detailed, then efficient uni-directional methods already exist for linear and nonlinear field and pulse propagation [30,31].

Field and pulse propagation is at the heart of very much of the work undertaken in the nonlinear optics community; however they typically use the existence of metamaterials as a justification to explore its traditional interest in pulse propagation with unusual material parameters. It is not uncommon to see publications on pulses and solitons and their variants in negative refractive index waveguides, for example; there seems rather less interest in transformation designs and metamaterials implemented as optical systems in their own right. Further, in acoustics nonlinearity is fairly ubiquitous and unavoidable [32], *something* needs to be achieved [33,34] to allow nonlinearity to be handled easily by T-Design processes. But, given the theoretical complications even in simple cases [27], the pertinent questions are very much what systems are treatable, and what interesting or practical results might actually be achieved?