Comment on ‘Reply to comment on “Perfect imaging without negative refraction”’

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**Abstract.** Whether or not perfect imaging is obtained in the mirrored version of Maxwell’s fisheye lens is debated in the comment/reply sequence (Blaikie 2010 *New J. Phys.* 12 058001; Leonhardt 2010 *New J. Phys.* 12 058002) discussing Leonhardt’s original paper (Leonhardt 2009 *New J. Phys.* 11 093040). Here, we show that causal solutions can be obtained without the need for an ‘active localized drain’, contrary to the claims made by Leonhardt (2010 *New J. Phys.* 12 058002).

R J Blaikie (RJB) notes in [1] that Ulf Leonhardt’s (UL) setup in [3] incorporates an ‘active localized drain’ at the image point. It is this drain, modeled as a phase-delayed mirror image of the source, that provides the sub-wavelength detail of the source’s image. RJB showed that a steady-state numerical simulation of the fields without the drain did not show the perfect super-resolution image of the source. In response, UL noted [2] that steady-state solutions neglect causality and that inclusion of a sink solves the problem of energy buildup.

We now address both of UL’s concerns about RJB’s simulations using a *time-domain* numerical solution with a source only active for a finite time. In figures 1 and 2 the results from such a simulation, calculated using the open source MEEP [4] implementation of the finite difference time domain (FDTD) [5], are shown. In FDTD, the real-valued electric and magnetic fields are defined over space, and an algorithm is applied that propagates these fields, step by step, forwards in time. It is thus explicitly causal, and entirely independent of any decomposition into plane waves or modes.

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Figure 1. Snapshot of the electric field $E_z$ from a simulation of the cylindrical mirrored fisheye, as the light first reaches the image point. Parameters are taken from RJB but with zero losses: $n(r) = 2/(1 + (r/r_0)^2)$ for $r_0 = 10 \mu m$, $f = 100$ THz (i.e. $\lambda_0 = 3 \mu m$).

Figure 2. Time history of the simulation in figure 1 showing the field $E_z$ along the $x$-axis. The intensity full-width at half-maximum (FWHM) of the source and image(s) are given, and can be compared to either $\lambda_0$ or the local wavelength ($\lambda_0/n \simeq 2.3 \mu m$) at the image point. Further bounces back and forth gradually degrade the image quality, and more so for briefer source durations.

The point-like source used is independent of all other properties of the simulation\textsuperscript{2}. We follow UL and RJB and use a frequency-independent refractive index profile, so there is no temporal dispersion. Our simulation therefore correctly tests for the geometric response and achievable spatial resolution, irrespective of the fact that transients are used instead of steady states. Figure 2 shows that the image is not as sharp as the source, and matches the steady-state results of RJB [1].

We do not include an active drain in our simulations because we believe it is unlikely to form part of any actual device, e.g. if this mirrored fisheye replaced the elliptical cavity used in

\textsuperscript{2} If there were e.g. a spatially separated source/active drain pair, we would have to ensure that any desired correlations between them remained consistent with causal signaling.
lamp-pumped lasers. Active drains often appear in the literature when systems with sources are
designed using folded-space or mirror-imaged transformations, e.g. the transformation optics
slab lens [6]. However, some authors insist that such active drains are unphysical and/or
mathematically ambiguous [7]–[10]. RJB was able to replace the drain in his steady-state
simulation with a carefully phased source [1], but this will fail in general for both time-domain
simulations and physical devices [11]. Whatever the method, we consider achieving super-
resolution by such means to be of little utility, since it requires a customised element to enhance
and ‘image’ the field at each precisely tuned pixel.

In summary, despite the claims in [2], causality does not require the presence of an active
drain, irrespective of whether or not an active drain might be otherwise useful.

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