Perfect imaging without refraction?

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New Journal of Physics 13 (2011) 125006 (5pp)
Received 7 October 2011
Published 8 December 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/12/125006

Abstract. Recent work suggesting that ‘perfect’ far-field imaging is possible using Maxwell’s fish-eye lens (Leonhardt 2009 New J. Phys. 11 093040) has raised a number of questions and controversies about the nature of imaging and field localization in inhomogeneous media. In this brief paper we present analogous results for a purely reflector-based imaging system—an elliptical cavity. With a source at one focus of the ellipse we show that sub-wavelength field localization can be achieved at the other focus when an active ‘drain’ is present there, but not without it. Does this show that far-field ‘perfect’ imaging is possible even without refraction (negative or positive)? Unfortunately not, giving further evidence that these are solely drain-induced effects.

The prediction of super-resolution far-field imaging with negative-refractive index flat lenses [1] raised the awareness of the optics and electromagnetic communities to a range of unusual possibilities if such materials could be found or engineered in the form of metamaterials; there has subsequently been a great deal of work undertaken to realize such systems, either using plasmonic near-field analogues [2, 3] or various metamaterial-based systems [4, 5].

But the unexpected prediction that similar super-resolution might be possible without negative refraction in a Maxwell fish-eye lens system [6] has the potential to have an even more profound impact on optical sciences and technologies; the materials required to manufacture such inhomogeneous refractive optical systems are already available in nature or easily engineered, and initial proof-of-concept results at microwave frequencies have shown interesting results [7].

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This work has not been without controversy, with a number of authors questioning the nature of the ‘perfect’ imaging that has been predicted in the theory, analysis and experimental investigations of Maxwell’s fish-eye and related refractive lenses [8–15]. There is now agreement that the field localization at and around the imaging point(s) requires a structured antenna or ‘drain’ of some kind to be present, as is the case in recent experiments [7]. However the decoupling of the effects of the inhomogeneous drain(s)—with sub-wavelength dimensions—from the inhomogeneity of the fish-eye lens itself—with supra-wavelength dimensions—is not straightforward, and more work is required in order to obtain a better understanding of the true nature of the super-resolution field localization in such systems. The role and nature of reflections in mirror-enclosed resonant-cavity systems is also a topic
Figure 3. Steady-state electric field profiles in the elliptical cavity excited by an ideal current source at the left-hand focus and without an ideal active drain at the right-hand focus. (above) The z-axis directed electric field, $E_z$, is plotted on a linear color scale (arbitrary units), and (below) the field strengths are depicted on a three-dimensional surface plot. Note that the field localization at the image point is now diffraction limited.

of current debate, with strong arguments put forward that ‘perfect’ imaging is not achievable with an ideal mirror on its own [16] (i.e. that the graded index fish-eye is a necessary component) or that the imaging properties of the dispersionless fish-eye lens is analogous to that of a simple mirror-enclosed spherical cavity [17] (i.e. the graded-index fish-eye is a distraction). Is there something special about the class of graded-index lenses that Maxwell’s fish-eye belongs to—also including popular Eaton [18] and Luneberg [19] lenses—or are the effects all attributable to the field-localising effects of the ‘drain(s)’ and the properties of the resonant cavity?

To address these issues a simple situation has been studied where all refraction has been removed and in this brief paper results are presented for the imaging characteristics of a purely reflective imaging system, namely an enclosed elliptical cavity shown schematically in figure 1. The imaging performance of a much simpler purely reflective system—a spherical reflective cavity—has already been studied and is the focus of some of the controversy in this field [12, 13]; the co-location of the source and imaging point at the centre of a such a spherical cavity makes interpretation difficult, and disagreement remains about the results [12, 13]. By using an elliptical cavity here the source and image points are decoupled without the need to add inhomogeneous refractive index distributions, which allows the simple question to be asked: is it possible to achieve ‘perfect’ imaging without refraction?

The cylindrically-symmetric free-space system (homogeneous refractive index $n = 1$ within the cavity) studied here (figure 1) is elliptical with a 4-cm long major axis and a 2-cm long minor axis; it is enclosed by perfectly reflecting walls. A 50 GHz ideal line current source (free-space wavelength $\lambda = 0.6 \text{cm}$) is located at the left-hand focus, $x = -1.73 \text{cm},$
Figure 4. Line traces of the $z$-axis directed electric field strength, $E_z$, taken along the $x$-axis ($y = 0$) for cases with (above) and without (below) an active drain at the image point.

$y = 0$, and finite-element numerical modeling [20] has been used to determine the steady-state electromagnetic fields within the mirror-enclosed region. The field profiles are compared both with or without an active drain [6, 8, 9] at the right-hand focus, $x = +1.73$ cm, $y = 0$, to determine the nature of the field localization at this point under these contrasting conditions. The active drain is simulated by another ideal current source driven in phase with the real source, with the same amplitude; it is noted that more sophisticated active or passive drain models have been studied by other authors [11, 21], including the effects of multiple sources and drains located within sub-wavelength domains around the focal points, but the essential field-localization properties of such systems remain unchanged compared to the idealized drain model used here, which is retained in order to compare results directly with the early work on the subject [6, 8, 9].

Figure 2 shows the simulated distribution of the electric field magnitude, $E_z(x, y)$, in the system for the case where there is an active ‘drain’ located at the right-hand focus, with
the equivalent field distribution for the drain-free case presented in figure 3. Line profiles for
the electric field along the x axis, $E_z(x, 0)$ are compared for both cases in figure 4. The imaging
characteristics of this system are very similar in nature to those we have reported previously
for the Maxwell fish-eye system [8], with sub-wavelength field enhancement only observed
for situations where there is a strong, sub-wavelength inhomogeneity at the image point (the
‘drain’ in this case), see figures 2 and 4 (upper). Without a drain, the fields around the right-hand
focus are distributed over a diffraction-limited area, see figures 3 and 4 (lower), as is the case is
drain-free fish-eye lenses [8].

It is very clear from these figures, as well as from much other work presented recently
[8, 11, 12, 14], that the sub-wavelength field enhancement at or around the image point only
occurs when a drain is present and, as shown here, an inhomogeneous refractive lens (e.g. a
fish-eye) is not even necessary. Whether the focusing is due to refraction or reflection the nature
of the ‘perfect’ imaging that has been the case of much recent excitement is solely due to drain-
induced effects. Hence it can be concluded that ‘perfect’ far-field imaging in a linear optical
system is not possible without negative refraction—or even without any refraction.

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New Journal of Physics 13 (2011) 125006 (http://www.njp.org/)