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Invited Paper

Advances in Imaging Beyond the Diffraction Limit

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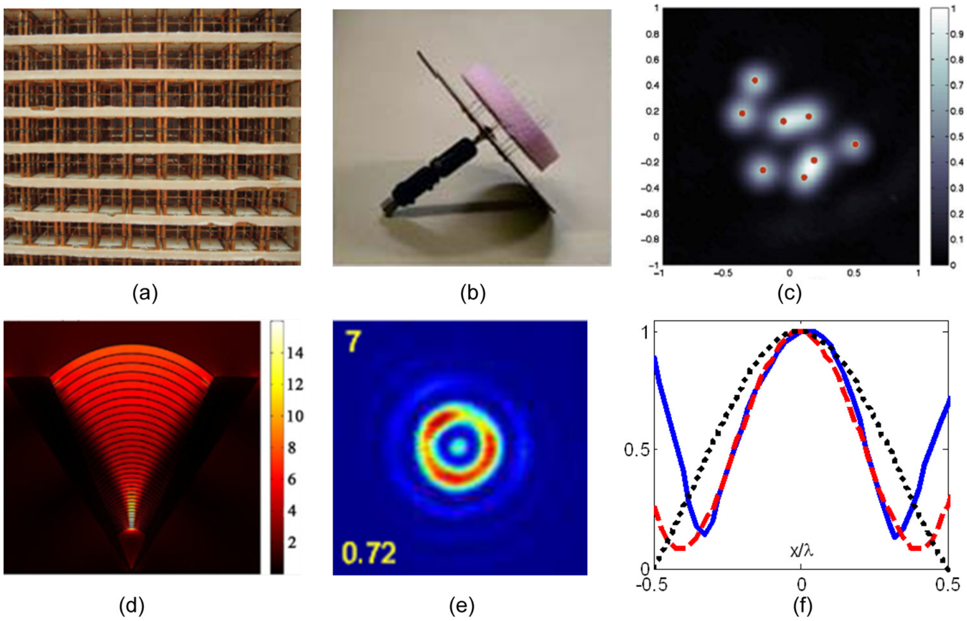
George V. Eleftheriades, Fellow, IEEE



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Advances in Imaging Beyond the Diffraction Limit

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(Invited Paper)

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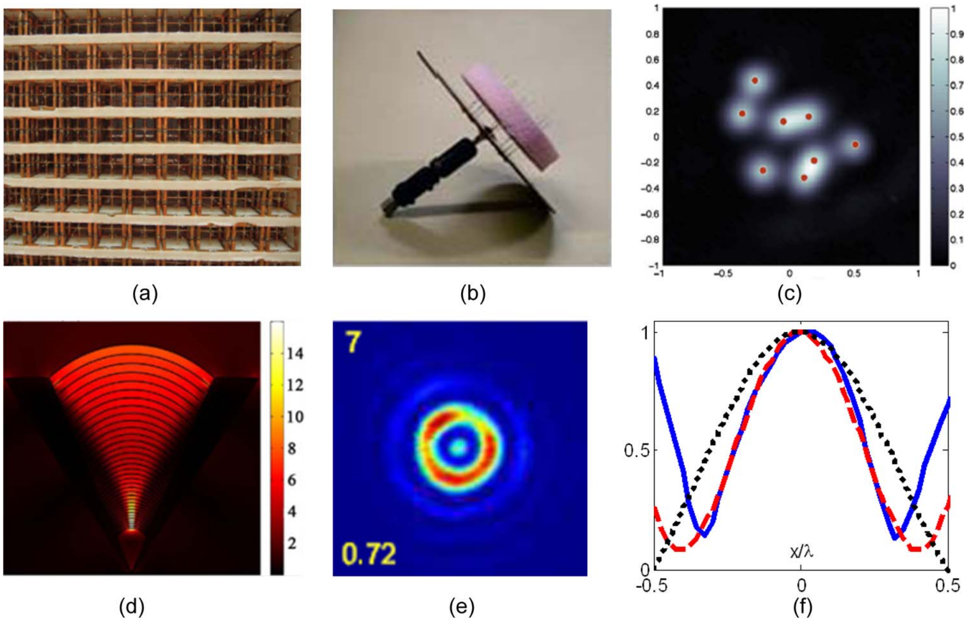
Abstract: Considerable research has been devoted to the development of imaging apparatus capable of high-resolution imaging beyond the diffraction limit. Innovative subdiffraction imaging systems have been proposed and successfully demonstrated. These systems either focus the electromagnetic near-field more tightly than a Hertzian dipole or resolve the electromagnetic far-field beyond Abbé's diffraction limit and, hence, can be termed subdiffraction imaging systems. This paper reviews major advances in the field of subdiffraction imaging in the year 2011, along the research fronts of superlenses, hyperlenses, metascreens, and superoscillations.

Index Terms: Imaging systems, subwavelength resolution, diffraction limit, metamaterials.

1. Superlens

Our review on progress in subdiffraction imaging in the year 2011 begins with the superlens, as it can be argued that Pendry's proposal of the superlens in year 2000 [1] revived research interest in the field of subdiffraction imaging. Pendry showed that a negative index slab (henceforth called the superlens) not only gives rise to negative refraction but can actually amplify evanescent waves and, thus, restore high-resolution details, which are inaccessible by classical imaging systems. In 2004, Grbic and Eleftheriades demonstrated superlensing for the first time with a 2-D microwave transmission-line metamaterial [2]. A year later, Fang *et al.* demonstrated optical subdiffraction imaging, following Pendry's suggestion of using a thin silver slab as a poor man's superlens for TE waves [3].

While the initial superlenses were restricted in terms of the object wave's polarization and direction of incidence, much effort has been directed toward making a 3-D, isotropic, polarization independent superlens. The transmission-line metamaterial emerged as a viable candidate (due to its low loss) for building such a superlens in the microwave regime. In 2009, Iyer and Eleftheriades extended the transmission-line superlens into 3-D in a volumetric fashion [4]; in 2011, Rudolph and Grbic used a transmission-line inspired platform to demonstrate the first 3-D, fully isotropic, polarization independent superlens [5]. They fabricated their superlens using a 3-D stereolithographic technique [see Fig. 1(a)] and showed that their superlens attained a field intensity focal width of approximately 0.17λ at an image distance of 0.15λ and at 1.51 GHz. A wide subdiffraction focusing bandwidth of over 13% has also been observed.



(a) (b) (c)

(d) (e) (f)

Fig. 1. Progress in subdiffraction imaging. (a) A frontal view of the microwave isotropic superlens [5, Fig. 6]. (b) A metascreen monopole array probe head inset of [17, Fig. 12]. (c) 2-D near-field subdiffraction imaging with the metascreen in (b). Most scatterers (labeled as red dots) are resolved with the metascreen, while a diffraction-limited probe failed to resolve any of them [17, Fig. 14(a)]. (d) Full-wave simulation of a trumpet hyperlens, showing subdiffraction electric field concentration at the bottom end of the trumpet [12, Fig. 4(d)]. (e) A measured superoscillatory focal pattern constructed by the optical eigenmode approach. The central peak has a spot width 72% of the diffraction limit (part of [25, Fig. 8]). (f) In-waveguide experimental subdiffraction focusing at a 5λ focal distance, comparing the measured (blue, solid), and simulated (red, dash) field profiles with the diffraction limit (black) (adapted from [22, Fig. 10]).

A related work by Kehr *et al.* [6] applies the superlensing effect to improve imaging resolution at mid-IR frequencies. Using a perovskite-based superlens, Kehr *et al.* demonstrated resolution improvement in a near-field scanning setup, compared to when the superlens was absent. The group demonstrated a resolution of $\lambda/14$ at the extreme near-field—at an image distance of 30 nm (around $\lambda/450$). While the involvement of a near-field probe and a reflective microscopic modality means the overall imaging system should not be considered as a simple superlens, the group distinguished probe-resonant effects from the superlensing effect and showed that superlensing was responsible for the observed resolution improvement.

2. Hyperlens and Related Developments

While the superlens forms an image of an object in the near field, the hyperlens images a near-field object into the far-field with subdiffraction resolution. Independently proposed by Jacob *et al.* [7] and by Salandrino and Engetha [8], the hyperlens is an anisotropic metamaterial exhibiting a hyperbolic dispersion property, which enables it to convert an object's evanescent waves into propagating waves, then image them into the far-field. The hyperlens has seen various developments in year 2011. Zhang *et al.* proposed theoretical extensions and designed a hyperlens with negative μ_ϕ and ρ_z [9]. They synthesized the necessary electromagnetic properties with an S-string-patterned metamaterial, performed simulations and experiments in the microwave range, and demonstrated a subdiffraction resolution of $\lambda/10$—an appreciable improvement over the initial optical demonstration where a resolution of about $\lambda/3$ was achieved [10].

On the optical front, the Wuhan University group of Zheng *et al.* [11] and the Lanzhou University group of Meng *et al.* [12] investigated using the hyperlens in reverse—to focus an impinging plane wave into a subdiffraction spot. The Wuhan group coupled an immersion lens with a traditional hyperlens, and showed through simulations that the system is capable of forming a focus with a spot size of $\lambda/11$. The Lanzhou group proposed the trumpet hyperlens, which is a sectorized hyperlens with its layered curves redesigned with a transformation optics approach. They showed in simulation [see Fig. 1(b)] that their design funnels a normally incident plane wave toward a central spot down to 6 nm—or $\lambda/60$—in size. A successful experimental demonstration on this front would be of significant interest to the fields of subdiffraction imaging and lithography.

3. Metascreens

Besides efforts toward achieving subdiffraction imaging using metamaterials, there is also prevalent work toward forming subdiffraction focal spots—and subsequently images—with subwavelength structured surfaces, which we will collectively term metascreens. A metascreen is an electromagnetic surface upon which one can launch an electromagnetic wave, which evolves into a subdiffraction spot at a set distance away from the surface. The principle was first proposed by Merlin [13], and a working device was first proposed by Wong *et al.* [14] based on a near-field hologaraphic point of view. The field of metascreens has since seen constant development. Grbic *et al.* summarized their research effort in a work in 2011 [15]. They solved an inverse electromagnetic problem to find the spatially varying surface impedance along the metascreen, then synthesized the impedance surface using current strips and current rings. With their metascreen, they calculated ultratight focusing to below $\lambda/15$, at a focal length of $\lambda/15$. Previous experiments on similar designs from Grbic *et al.* have yielded similar subdiffraction focusing results [16] in the microwave regime.

Markley and Eleftheriades adopted a different perspective to designing metascreens [17]. They employed a "shifted-beam" theory and designed the metascreen by optimizing the near-field interference of a 2-D antenna array. Using this approach, they proposed dipole and monopole arrays, and experimentally demonstrated focusing and imaging capabilities about 50% reduced from that of a diffraction-limited system [see Fig. 1(b) and (c)]. While their system resolution—experimentally found to be 0.25λ to 0.3λ—and their obtained focal widths are higher than in the work by Grbic *et al.*, these focal widths are obtained at a working distance of a quarter wavelength—much longer than the range considered by Grbic *et al.* and much improved over the working distance of most near-field probes. This work can be carried into the optical regime, with similar resolution improvement ratios achieved for 1-D subdiffraction imaging [18].

A related work from the group of Pan *et al.* should also be mentioned. In their work, a multistage plasmonic lens was proposed, which allowed the extraordinary transmission of ultraviolet light through a structured nanoscale aperture, thus forming a tight spot with an intensity full width and half maximum of 45 nm at 10 nm from the lens [19]. The resolution was then further improved to 22 nm due to the thermal threshold of the photoresist 10 nm away from the lens. Although the multistage plasmonic lens (which can be viewed as a form of metascreen) was diffraction-limited in the near-field sense according to the definition given in our abstract, it nonetheless greatly enhanced the transmitted power while maintaining, for the most part, the field localization of a same-shaped central aperture. It can thus be viewed as a use of the metascreen in a practical lithographic environment.

4. Superoscillation

Whereas superlenses, hyperlenses, and metascreens employ evanescent waves which limit either their object-to-device or their device-to-image distances, a newly emergent class of superoscillation-based devices are unhindered by these distance limitations. Superoscillation refers to a wave phenomenon whereby within an interval of a waveform, rapid oscillations occur which exceed the waveform's highest constituent frequency. High-energy sidebands coexist with such superoscillations. However, if one can tolerate the sidebands, one can record subdiffraction features with superoscillatory propagating waves, and thereby image them into the far-field.

Superoscillations were first studied as a mathematical property of the prolate spheroidal wave functions [20], which have been proposed as candidates to improve image resolution in a post-processing scheme [21]. Recently, Wong and Eleftheriades [22] related superoscillation and Schelkunoff's superdirectivity as dual effects in the spatial and spatial-frequency domains. Leveraging this analogy, Wong and Eleftheriades used methods of antenna design to synthesize superoscillation waves, and demonstrated microwave subdiffraction focusing at a working distance of five wavelengths [see Fig. 1(f)] [22]. The periodic nature of their design allowed them to demonstrate superoscillation within a waveguide environment, which greatly compacted the lateral electrical size of their device. In a parallel stream of work, Huang and Zheludev numerically synthesized superoscillations using prolate spheroidal wave functions [23]. More recently, their collaboration with Baumgartl *et al.* resulted in a demonstration of optical subdiffraction focusing using a superoscillatory waveform constructed from optical eigenmodes, which in turn are formed from the superposition of Bessel beams [24], [25]. In their work, a subdiffraction field intensity lobe of 0.35λ was created at a focal length away from a focusing microscope objective [see Fig. 1(e)]. In a separate development, Makris and Psaltis theoretically and numerically studied the formation of diffraction-free superoscillatory waveforms, which directly beamed subdiffraction features into the far-field [26].

References

[1] J. B. Pendry, “Negative refraction makes a perfect lens,” *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966–3969, Oct. 2000.

[2] A. Grbic and G. V. Eleftheriades, “Overcoming the diffraction limit with a planar left-handed transmission-line lens,” *Phys. Rev. Lett.*, vol. 92, no. 11, pp. 117403-1–117403-4, Mar. 2004.

[3] N. Fang, H. Lee, C. Sun, and X. Zhang, “Sub-diffraction-limited optical imaging with a silver superlens,” *Science*, vol. 308, no. 5721, pp. 534–537, Apr. 2005.

[4] A. K. Iyer and G. V. Eleftheriades, “Free-space imaging beyond the diffraction limit using a Veselago-Pendry transmission-line metamaterial superlens,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 6, pp. 1720–1727, Jun. 2009.

[5] S. M. Rudolph and A. Grbic, “The design and performance of an isotropic negative-refractive-index metamaterial lens,” in *Proc. URSI Gen. Assembly Sci. Symp.*, Aug. 13–20, 2011, pp. 1–4.

[6] S. C. Kehr, Y. M. Liu, L. W. Martin, P. Yu, M. Gajek, S. Y. Yang, C. H. Yang, M. T. Wenzel, R. Jacob, H. G. von Ribbeck, M. Helm, X. Zhang, L. M. Eng, and R. Ramesh, “Near-field examination of perovskite-based superlenses and superlens-enhanced probe-object coupling,” *Nat. Commun.*, vol. 2, p. 249, Mar. 2011.

[7] Z. Jacob, L. V. Alekseyev, and E. Narimanov, “Optical hyperlens: Far-field imaging beyond the diffraction limit,” *Opt. Exp.*, vol. 14, no. 18, pp. 8247–8256, Sep. 2006.

[8] A. Salandrino and N. Engheta, “Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations,” *Phys. Rev. B*, vol. 74, no. 7, pp. 075103-1–075103-5, Aug. 2006.

[9] W. Zhang, H. Chen, and H. O. Moser, “Subwavelength imaging in a cylindrical hyperlens based on S-string resonators,” *Appl. Phys. Lett.*, vol. 98, no. 7, pp. 073501-1–073501-3, Feb. 2011.

[10] Z. Liu, H. Lee, Y. Xiong, C. Sun, and X. Zhang, “Far-field optical hyperlens magnifying sub-diffraction-limited objects,” *Science*, vol. 315, no. 5819, p. 1686, Mar. 2007.

[11] G. Zheng, R. Zhang, S. Li, P. He, H. Zhou, and Y. Shi, “A hyperlens-embedded solid immersion lens for beam focusing beyond the diffraction limit,” *IEEE Photon. Technol. Lett.*, vol. 23, no. 17, pp. 1234–1236, Sep. 2011.

[12] Q. Meng, X. Zhang, L. Cheng, P. Cao, Y. Li, H. Zhang, and G. Wang, “Deep subwavelength focusing of light by a trumpet hyperlens,” *J. Opt.*, vol. 13, no. 7, p. 075102, Jul. 2011, DOI:10.1088/2040-8978/13/7/075102.

[13] R. Merlin, “Radiationless electromagnetic interference: Evanescent-field lenses and perfect focusing,” *Science*, vol. 317, no. 5840, pp. 927–929, Aug. 2007.

[14] A. M. H. Wong, C. D. Sarris, and G. V. Eleftheriades, “Metallic transmission screen for sub-wavelength focusing,” *Electron. Lett.*, vol. 43, no. 25, pp. 1402–1404, Dec. 2007.

[15] A. Grbic, R. Merlin, E. M. Thomas, and M. F. Imani, “Near-field plates: Metamaterial surfaces/arrays for subwavelength focusing and probing,” *Proc. IEEE*, vol. 99, no. 10, pp. 1806–1815, Oct. 2011.

[16] A. Grbic, L. Jiang, and R. Merlin, “Near-field plates: Subdiffraction focusing with patterned surfaces,” *Science*, vol. 320, no. 5875, pp. 511–513, Apr. 2008.

[17] L. Markley and G. V. Eleftheriades, “Meta-screens and near-field antenna-arrays: A new perspective on subwavelength focusing and imaging,” *Metamaterials*, vol. 5, no. 2/3, pp. 97–106, Jun.–Sep. 2011.

[18] Y. Wang, A. M. H. Wong, L. Markley, A. S. Helmy, and G. V. Eleftheriades, “Plasmonic meta-screen for alleviating the trade-offs in the near-field optics,” *Opt. Exp.*, vol. 17, no. 15, pp. 12 351–12 361, Jul. 2009.

[19] L. Pan, Y. Park, Y. Xiong, E. Ulin-Avila, Y. Wang, L. Zeng, S. Xiong, J. Rho, C. Sun, D. B. Bogy, and X. Zhang, “Maskless plasmonic lithography at 22 nm resolution,” *Sci. Rep.*, vol. 1, p. 175, Nov. 2011.

[20] D. Slepian and H. O. Pollak, “Prolate spheroidal wave functions, Fourier analysis and uncertainty I,” *Bell Syst. Tech. J.*, vol. 40, pp. 43–63, 1961.

[21] C. W. Barnes, “Object restoration in a diffraction-limited imaging system,” *J. Opt. Soc. Amer.*, vol. 56, no. 5, pp. 575–578, May 1966.

[22] A. M. H. Wong and G. V. Eleftheriades, “Sub-wavelength focusing at the multi-wavelength range using superoscillations: An experimental demonstration,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4766–4776, Dec. 2011.

[23] F. M. Huang and N. I. Zheludev, “Super-resolution without evanescent waves,” *Nano Lett.*, vol. 9, no. 3, pp. 1249–1254, Mar. 2009.

[24] J. Baumgartl, S. Kosmeier, M. Mazilu, E. T. F. Rogers, N. I. Zheludev, and K. Dholakia, “Far field subwavelength focusing using optical eigenmodes,” *Appl. Phys. Lett.*, vol. 98, no. 18, pp. 181109-1–181109-3, May 2011.

[25] M. Mazilu, J. Baumgartl, S. Kosmeier, and K. Dholakia, “Optical eigenmodes; Exploiting the quadratic nature of the energy flux and of scattering interactions,” *Opt. Exp.*, vol. 19, no. 2, pp. 933–945, Jan. 2011.

[26] K. G. Makris and D. Psaltis, “Superoscillatory diffraction-free beams,” *Opt. Lett.*, vol. 36, no. 22, pp. 4335–4337, Nov. 2011.