SUPERLENS-BASED NANOSCALE IMAGING

SOUMEN MANDAL

Since the discovery of the superlens (a lens that uses metamaterials to go beyond the diffraction limit), optical imaging for nanometer-sized objects has become possible. A superlens basically aids in the resolution improvement of an image, which is the primary essence to observe subwavelength features (in the nanometer range). The subwavelength features are missed in conventional optical imaging systems due to the diffraction limit of light. In the 21st century, various methods have been proposed to conduct nano-imaging using superlenses. This article provides a basic insight of nano-imaging using superlenses, various problems and limitations in nanovision, and the latest improvements in research.

IMAGE COURTESY OF STOCK.XCHNG/OPINTO

An introduction to nanoscale imaging

There is no denying the fact that systems for imaging at the nanoscale have profuse significance in today's world of miniaturization. Nanoscale imaging or nanoparticle vision has a wide variety of applications ranging from biological diagnostics to quantum electronics. Nanoscale imaging refers to the vision of particles or particle aggregates that have at least one dimension in the scale of nanometers. Nano-imaging systems rely on the symbiotic integration of a number of scientific disciplines such as nanotechnology, photonics, electronics, and mechanical engineering.

Nanoscale imaging systems are used for the diagnostics of complex cellular structures in biological and health-care assays. Researchers at Oak Ridge National Laboratory have used nanoscale imaging to investigate cellular function at the level of individual proteins and to study the interaction of nanomaterials with biological systems. Such study of systems aided by nano-imaging opens up new vistas to the knowledge of cell metabolic rate. Cell metabolic rate is a prime indicator of cellular dysfunction due to malignancy or other related ailments. In the field of physics and molecular electronics, nanoscale imaging aids in establishment of physical phenomenon and validation of the same.

Very recently, researchers at Brookheaven National Laboratory have developed a nanovision technique to track the exact reactions occurring in lithium-ion cells. In an electrochemical cell, a chemical reaction is used to generate electric energy. The exact knowledge of a cell reaction enhances the cell life and support time of the cell.

In the arena of mechanical engineering, nano-imaging is used to track surface properties. Surface characterization is an important step toward the development of artificially tailored surfaces. The lotus leaf, water-repellant windshields of automobiles, and antibacterial surfaces are classic examples of naturally created surfaces. In these surfaces, already existing nano patterns render a specific property to them. For instance, a lotus leaf or the water-repellant windshield of an

Digital Object Identifier 10.1109/MPOT.2013.2282165
Date of publication: 6 March 2014

automobile is strongly hydrophobic. Similarly there exist few surfaces like the shark fin, which possesses microbial resistance due to the nanoscale patterns on it. Mimicry of such surfaces for the generation of artificially tailored ones (which have similar functionality to the natural ones) requires nanovision.

It can thus be said that the applications and demand for nanoscale imaging systems are at a peak. A variety of systems and paradigms exist for nanoscale imaging, and the most popular ones include electron microscopy (EM), the scanning tunneling microscope (STM), the atomic force microscope (AFM), nanoscale spectroscopy, and tip-enhanced Raman scattering (TERS). Each has their own limitations as stated in Table 1.

In the early 21st century, the nanoscale imaging technique of "superlens-based imaging" was introduced. In conventional optical lenses, the imaging of subwavelength features are not possible due to the diffraction of light. The superlens abdicates the problem of overcoming the diffraction of light, thus rendering subwavelength imaging feasible.

Technical limitations of nanoscale imaging

Nano-imaging refers to the visualization of nanoparticles and structures with adequate magnification and resolution. Unlike normal optical microscopes that focus on magnifying an image to view the minute details of the specimen, nano-imaging combines both the effects of magnification and resolution. At the nanoscale, whatever the magnification, the image remains blurred or invisible if proper resolution is not met.

Further, the technical limitation regarding resolution is enhanced due to the law of optics—that it is impossible to view an object that has dimensions less than the wavelength of light (half the wavelength for grazing incidence) source used for illuminating the object. For example, the wavelength of the visible spectrum lies in the range of approximately 400–700 nm. So it's obvious that particles having a footprint in the order of, or fewer than, 200 nm cannot be visualized under any circumstances using a normal optical microscope, regardless of the magnifying power.

THERE IS NO DENYING THE FACT THAT SYSTEMS FOR IMAGING AT THE NANOSCALE HAS PROFUSE SIGNIFICANCE IN TODAY'S WORLD OF MINIATURIZATION.

The resolution of imaging at the nanoscale is also affected by diffraction-induced scattering. At the nanoscale, the diffraction induced by nanoparticles to the incident light leads to the generation of evanescent waves. These evanescent waves carry vital information regarding minute details of the particles under imaging. But due to the fact that these waves decay at an exponential rate, unlike transmitted waves where power decay is sinusoidal, these waves are lost in the near field of the particles. Thus at far field distance (distances that are much higher than the wavelength of incident source), it becomes impossible to capture these lost waves. As a result, the subnanometer details are missed in imaging systems.

Table 1. Popular techniques used for nanoscale imaging and their limitations.

No.	Technique	Limitations
1	EM	1) Very high equipment cost. 2) Bulky equipment that needs sophisticated storage and maintainence. 3) Requirement of very high voltage supply. 4) Sample preparation is tedious, as it has to been seen in a vacuum.
2	STM	Suitable for conducting and semiconducting materials only.
3	AFM	Needs very sensitive handling of the instrument.
4	Nanoscale spectroscopy	Suitable for procuring chemical information and material characteristics.
5	TERS	Contact-based method. Pressure on the sample from the probe tip may be detrimental to the sample.

Basic working of superlens for nanoscale imaging

Superlenses generally possess a negative index of refraction. A negative refractive index-based material is not available in nature and is artificially tailored. Such materials exist in theory in a myriad of interfacial and structural forms, but practical applicability and fabrication of such materials is very limited.

A metamaterial-based superlens with negative refractive index acts as an evanescent to a propagating wave converter. Thus the evanescent waves, which decay after traveling out from the near field, are converted into propagating waves by the material. As propagating waves can travel to the far field, so the information in the propagating waves generated from the evanescent waves are not lost when they reach the far field. Thus subwavelength-based features become clearly visible. Different researchers have proposed prototype superlenses for nanoscale imaging. The reported approaches are stated in the following section.

Advancements in superlens-based imaging

Superlenses are able to compensate the exponential decay of evanescent fields that carry vital information about the minute details of an object. The first superlens came up in 2004. It had a negative index of refraction and could provide a resolution three times better than the diffraction limit. However, the lens was suitable for microwave frequencies. In 2005, a nonnegative refractive index-based superlens was demonstrated. The lens could enhance the evanescent modes by surface plasmon coupling. Developments in superlenses functional in nonoptical frequencies proceeded from 2005 to 2007. The progress included the use of different geometrical configurations of the lenses and the use of varying materials for lens fabrication.

The advancements in the previous paragraph dealt with magnifying superlenses in the nonvisible spectrum. In 2007, a group from the University of Maryland reported a magnifying superlens that could be used for optical microscopy in the visible frequency range. The group also integrated its system into an optical microscope to view nanometer-sized particles. The invention was noteworthy due to the fact that it uses a visible light source, thus aiding in the vision and imaging of nanoparticles, which would not be possible for other frequency ranges.

The preliminary approach used by the research group from the University of Maryland at College Park emphasizes the use of a negative refractive index metamaterial-based superlens to improve resolution at the nanoscale and could achieve a resolution of 70 nm using their fabricated instrument.

In the experimental setup proposed by the group, a thin gold layer was deposited on a glass substrate. Thin polymethy methacrylate (PMMA) rings were fabricated on the surface. It was observed that the PMMA-Au interface acts as a negative refractive index-based media under plasmonic illumination. So it is evident that the evanescent waves, due to the illumination of the nanoparticles using plasmons in the near field, gets transformed into propagating waves and are carried into the far field. The setup was then placed on the object plane of a conventional optical microscope to render magnification. The ultra-high-resolution images were thus magnified by a normal optical microscope to have a clear insight of the nanoparticles. The setup of the prototype is as shown in Fig. 1.

The results obtained by using the setup shown in Fig. 1 are presented in Fig. 2. Fig. 2(a) shows the sample particles observed using an AFM, and Fig. 2(b) shows the particles as seen under the stated setup. It can be observed that the setup employing the superlens to view the image of sample particles bears a resolution that is comparable to the AFM-based images.

In 2008, a new strategy of using nanoholes was used to concentrate the optical energy into subwavelength hot spots. This technique didn't use superlens-based criteria in its working principle. The subwavelength spots that contain vital information about the minute details of an image could only be formed near the nanohole array (at about few tens of wavelength). The illustration is shown in Fig. 3.

A three-dimensional metamaterial-based nanolens was proposed in 2010, which was composed of thin gold nanowires embedded in a porous alumina matrix. The proposed prototype could image finer details of large objects at significant distances from the lens.

A nonconventional method of using SiO_2 microspheres was proposed in 2011 to overcome the diffraction limit and image subwavelength features. This setup uses white light as a source, and the nanospheres act as far-field superlenses to overcome the diffraction limit. The proposed setup is depicted in Fig 4. The microspheres superlenses collect the underlying near-field information, magnify it, and then form a virtual image (which has same orientation as the object). The magnified virtual images thus could be captured at far field. The lens could achieve a maximum resolution of 50 nm.

Current state of research

In a current research scenario of nanovision using superlenses, the trend is shifting toward a combination of different lens geometries to achieve higher resolution gain. A research group from Taiwan has recently proposed a gain-assisted hybrid-superlens hyperlens for nano imaging. Though a theoretical validation has been performed in their published literature, it opens up new vistas toward research pertaining to superlenses with inherent gain capability.

In any hybrid superlens (a combination of different structural geometries), the lightwave energy incident on it

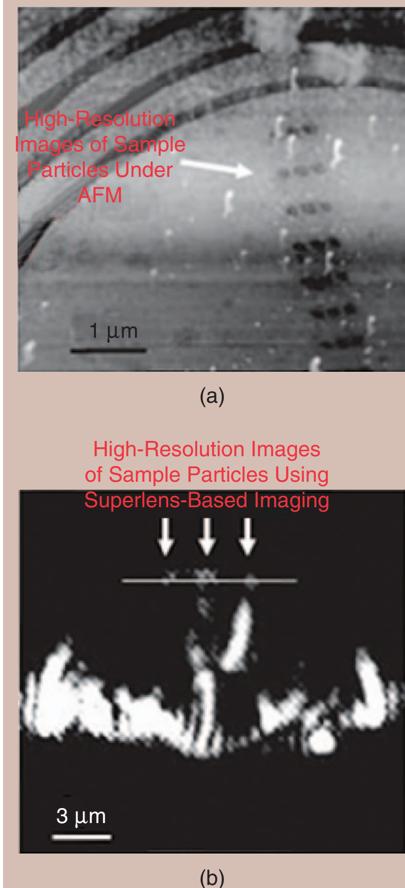

Fig. 2 (a) A high-resolution image of sample particles under an AFM. (b) High-resolution images of sample particles using superlens-based imaging. (From [I.I. Smolyaninov, Y.J. Hung, and C.C. Davis, "Magnifying superlens in the visible frequency range," *Science*, vol. 315, 2007, pp. 1699–1701]. Reprinted with permission from AAAS.)

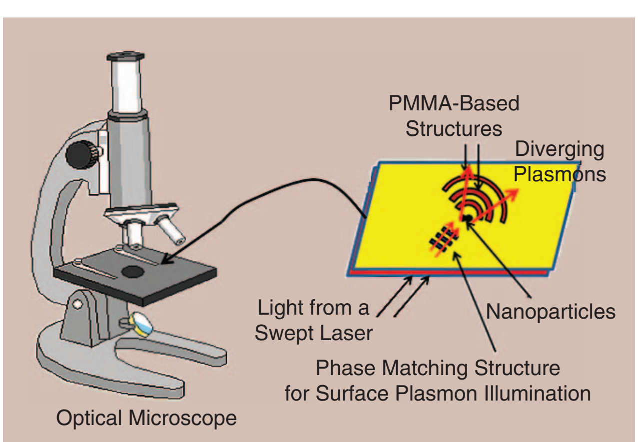

Fig. 1 The setup for the prototype for nanoscale imaging in the visible frequency range.

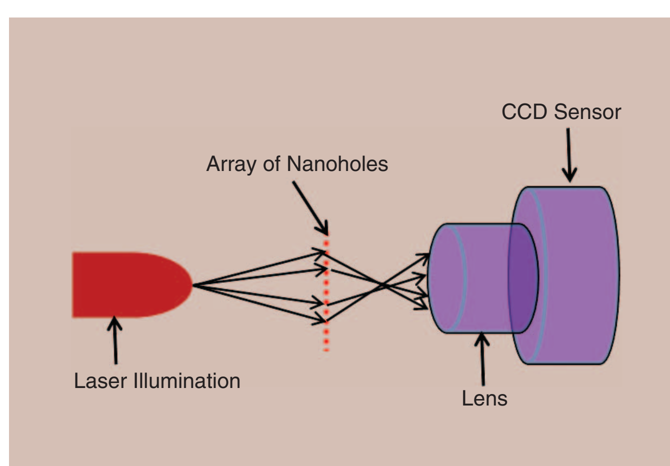

Fig. 3 Nanoscale imaging using an array of nanoholes.

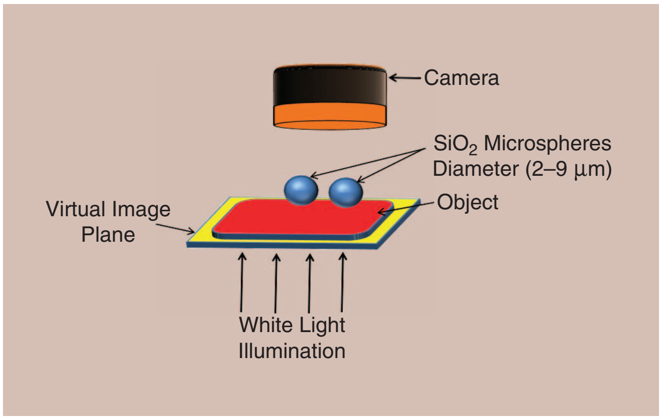

Fig. 4 An optical nanoscope using SiO_2 microspheres.

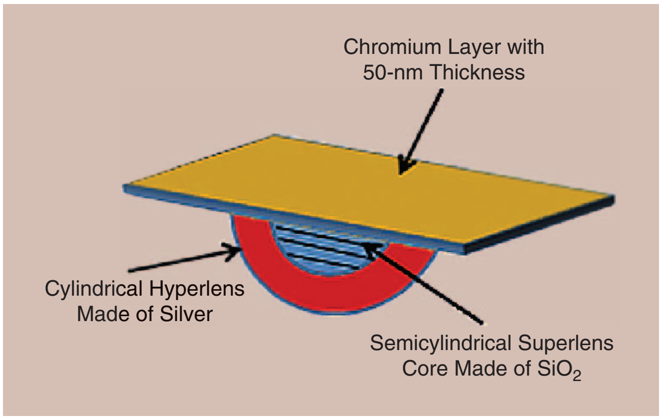

Fig. 5 A schematic for a hybrid superlens with magnification ability.

decays very fast. This problem can be resolved by the use of inherent gain assisting chemicals or substances in the lens. In the experiments conducted by the group, they used coumarin as a gain material. The structure of the lens consists of a semicylindrical superlens core as an upper part surrounded by a cylindrical-hyperlens shell as the lower part. In the lower part, coumarin doping is performed in order to enhance the gain. At the top, there is a metallic chromium layer with a thickness of 50 nm. The schematic is shown in Fig. 5. The researchers have claimed that as the size and geometry of their theoretical lens are practically realizable in today's nanofabrication scenario, such systems can be developed and integrated with objective lenses of microscopes.

Summary

It is understood that superlens-based nanoscale imaging has achieved significant popularity in research. Efforts to achieve higher resolution and magnification for imaging nanometer-sized objects using superlens is continuously improving. Though the technology is not yet implemented in industry, it can be expected that superlens-based nanoscale imaging will be on par with industrial applications with its other counterparts viz. EM, AFM, STM, among others, due to its low operating cost, robust system design, and noncontact-based measurement method. Because of the extremely high installation and operation costs of existing nanoscale imaging systems, it becomes out of reach for academic institutions, remote health-care diagnostic centers, and small-scale industries to procure and maintain such systems. The establishment of industrial-grade superlens-based nanoscale imaging instruments would lead to a revolution in the education, research, health-care, and manufacturing industries.

Read more about it

- E. Allen and L. Rathbun. (2005). Seeing nanostructures, National Nanotechnology Infrastructure Network. [Online]. Available: http://www.nnin.org/news-events/spotlights/seeing-nanostructures
- X. Zhang and Z. Liu, "Superlenses to overcome the diffraction limit," *Nature Mater.*, vol. 7, no. 6, pp. 435–441, 2008.
- J. Pendry, "Negative refraction makes perfect lens," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966–3969, 2000.
- D. O. S. Melville and R. J. Blaikie, "Super resolution imaging through a planar silver layer," *Opt. Exp.*, vol. 13, no. 6, pp. 2127–2134, 2005.
- 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, 2005.
- Y. Oshikane, T. Kataoka, M. Okuda, S. Hara, H. Inoue, and M. Nakano, "Observation of nanostructure by scanning near-field optical microscope with small sphere probe," *Sci. Technol. Adv. Mater.*, vol. 8, no. 3, pp. 181–185, 2007.
- U. Durig, D. W. Pohl, and F. Rohner, "Near field optical scanning microscopy," *J. Appl. Phys.*, vol. 59, no. 10, p. 3318, 1986.
- I. I. Smolyaninov, Y. J. Hung, and C. C. Davis, "Magnifying superlens in the visible frequency range," *Science*, vol. 315, no. 5819, pp. 1699–1701, 2007.
- 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, 2006.
- A. V. Zayats, I. I. Smolyaninov, and A. A. Maradudin, "Nano-optics of surface plasmon polaritons," *Phys. Rep.*, vol. 408, nos. 3–4, pp. 131–314, 2005.
- Z. Wang, W. Guo, L. Li, B. Luk'yanchuk, A. Khan, Z. Liu, Z. Chen, and M. Hong. (2011, Mar.). "Optical virtual imaging at 50 nm lateral resolution with a white-light nanoscope." *Nature Commun.* [Online]. Available: http://www.nature.com/ncomms/journal/v2/n3/full/ncomms1211.html
- Y. T. Wang, B. H. Cheng, Y. Z. Ho, Y.-C. Lan, P.-G. Luan, and D. P. Tsai, "Gain-assisted hybrid-superlens hyperlens for nano imaging," *Opt. Exp.*, vol. 20, no. 20, pp. 22953–22960, 2012.
- F. M. Huang, T. S. Kao, V. A. Fedotov, Y. Chen, N. I. Zheludev, and F. Huang, "Nanohole array as a lens," *Nano Lett.*, vol. 8, no. 8, pp. 2469–2472, 2008.

About the author

Soumen Mandal (somandal88@gmail.com) received the bachelor of technology degree with a major in electronics and electrical engineering from KIIT University, India, in 2010 and a master of technology in mechatronics from the Academy of Scientific and Innovative Research (AcSIR) India in 2012. He currently works as a scientist at Micro Systems Technology Laboratory, Council of Scientific and Industrial Research (CSIR)-Central Mechanical Engineering Research Institute, India. He is concomitantly serving as a faculty member at AcSIR University. He is a Member of IEEE, the Indian Science Congress Association, and the International Association of Engineers.