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From Traditional Lenses to Superlenses: a Revolution in Imaging Technology

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Abstract:

Since ancient times, lenses have been a crucial tool in human history. They were used in telescopes during navigation to determine the surrounding environment; in biology, lenses were incorporated into microscopes to magnify details invisible to the human eye. However, due to their design and structural characteristics, traditional optical lenses have inherent drawbacks, resulting in physical bottlenecks in their development. These include insufficient image detail, severe detail loss, and excessively large and heavy lens assemblies. In the 21st century, with the intersection of optical physics and nanotechnology, scientists proposed the concept of metamaterials and began developing metamaterial-based superlenses. The advent of superlenses has truly provided tools capable of clearly magnifying nanoscale details. This represents not only a breakthrough in optical physics but also a foreshadowing of the importance of interdisciplinary exchange. This article, through a literature review, illustrates the role that cutting-edge technologies and research directions in superlenses developed in other countries can play in enabling the development of superlenses in China.

Keywords: traditional lens, Fresnel lens , metamaterial , superlens , Empowerment Technology

1. Introduction

As an emerging planar optical technology, superlens achieves precise control of light waves through artificial structures at the micron level, breaking the limitations of traditional optics on the diffraction limit and achieving a resolution of 10-50 nm.

VG Veselago proposed the "perfect lens" theory, that is, negative refractive materials can amplify evanescent waves and restore all spatial frequencies, thereby breaking through the diffraction limit [1]. Negative refraction and plasmon super lenses continue to develop, and at the same time, "metasurfaces" have gradually become the mainstream paradigm for realizing planar optics (including metal lenses). Chinese researchers have also been empowered by these studies and have contributed their own achievements in the field of optical metasurfaces worldwide. Cui Tiejun's team proposed a "coding/digital/programmable metasurface" system to promote metasurfaces from static devices to controllable and reconfigurable devices, laying a methodology and device platform for the functionalization and systematization of subsequent metal lenses. [2] This paper, through a literature review, illustrates the stimulating effect of the development of superlenses in other countries on the development of superlenses in China. This article summarizes the development of superlens technology by predecessors, including the introduction of the concept of metamaterials to the mass production of physical superlenses. From exploring the enabling role of international development in superlenses for China, it extends to the current development status of China's optical technology and its future prospects. It promotes the organic integration of theoretical deepening and industrial empowerment, and helps further breakthroughs and application landing in this field.

2. Literature Review

2.1 Development of Traditional Lenses

In the early 17th century, the emergence of Galileo's telescope laid the foundation for today's lenses [3]. Basic telescopes magnify images by stacking lenses, which has promoted the development of astronomy to a certain extent. Microscopes also increase imaging details by stacking lenses.

However, traditional lenses, which utilize the phase accumulation of light propagation within a material to alter the wavefront of transmitted light, are unable to discern information shorter than the wavelength of light due to the diffraction limit. This results in blurred image details and an inability to resolve subwavelength structures. Their resolution is approximately 200 nm, and their maximum magnification is approximately 1000x. Traditional lenses also suffer from issues such as bulk, high mass, low numerical aperture, severe distortion, and aberrations, as shown in Figures 1 and 2.

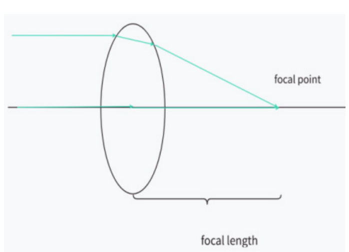

Figure 1. Conventional lens imaging

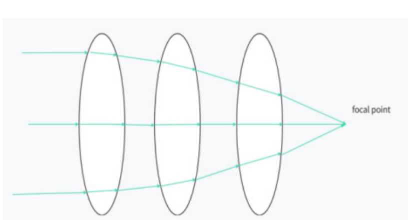

Figure 2. Multiple refraction imaging of a traditional lens group

2.2 Development of Fresnel Diffraction Lenses

To address these issues, the Fresnel lens, invented in 1822 by French physicist Augustin Fresnel, was originally designed for use in lighthouses. While preserving the curvature of a convex lens' optical surface, the Fresnel lens removes an integer multiple of 2π from the intermediate material. Using a sawtooth prism, it guides light within a specific spectral range, achieving a transition from a spherical lens to a flat lens (Figure 3). While this solves the bulk and mass issues of traditional lens systems, the diffraction limit causes the exponential decay of the evanescent wave, resulting in the loss of imaging details less than half a wavelength and the inability to achieve perfect imaging. This phenomenon dictates the resolution limit of traditional optical imaging systems. The diffraction limit of a Fresnel diffraction lens is still only 200 nm, and the maximum magnification is approximately 1000x (Figure 4).

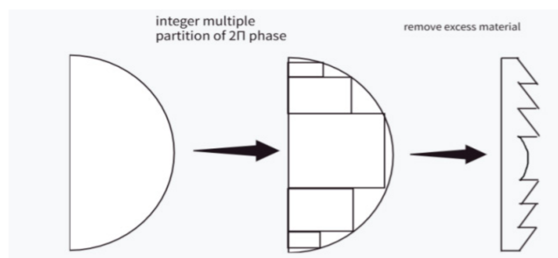

Figure 3. Transformation process from traditional lens to Fresnel diffraction lens

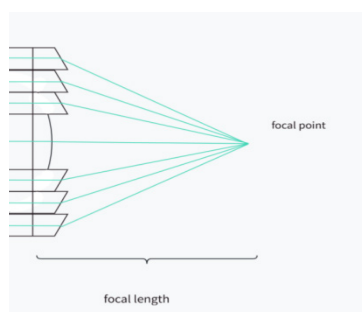

Figure 4. Fresnel diffraction lens imaging optical path

2.3 Discovery of metamaterials

Metamaterial Definition The term "metamaterial" was first proposed by Professor Rodger M. Walser to describe composite materials that do not exist in nature, are artificially manufactured, are three-dimensional, and have periodic structures [4]. Metamaterials are artificial materials with extraordinary physical properties that natural materials do not have. Metamaterials are designed with surrounding nanoscale patterns or structures to interact with light or other forms of energy in a way that does not exist in nature. Initially, due to its unique design, it allows

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light to reconverge on the other side of the metamaterial with very little absorption and reflectivity when it propagates through the metamaterial. Therefore, there will be some special phenomena, such as making objects difficult to observe (the idea of an invisibility cloak), as shown in Figure 5. However, the clever thing is that the super lens can interact with electric or magnetic fields.

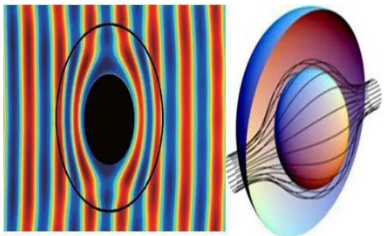

Figure 5. Schematic diagram of metamaterial

2.4 Concept of the Superlens

In 2000, Pendry proposed the idea of using negative refractive index materials to create a "perfect lens" [5]. This theory states that a superlens can not only focus light waves, but also extend the range of the "evanescent wave" that usually decays rapidly at the interface, thereby achieving imaging with subwavelength resolution. This idea marked the starting point of superlens research. Since then, the development of superlenses has entered a stage of rapid development, and various superlenses with different details have emerged.

2.4.1 Plasmonic Superlens

Plasmonic metalenses enhance evanescent waves through SPPs, enabling the transmission of spatial details smaller than $\lambda/2$. At a metal-dielectric interface, when the vibration frequency of incident light approaches that of free electrons in the metal, collective resonance occurs. This stimulates localized microcurrents on the surface of the structure, and the light field excites collective oscillations (SPPs) of electrons. These SPPs essentially extend the effective range of the evanescent wave, extending its propagation distance beyond its otherwise rapidly decaying state. This allows the transmission of subwavelength information that would otherwise be unable to reach the other side of the lens. Plasmonic metalenses utilize plasmon resonances on the metal surface to compensate for and enhance the evanescent wave, thereby restoring subwavelength information and achieving super-resolution imaging that surpasses the diffraction limit, resulting in sharper images and richer details.

2.4.2 Dielectric superlens

Metal lenses rely on metal plasmons (electron oscillations). Metals have strong absorption in the optical band, converting some light energy into heat, causing rapid attenuation of light intensity. Dielectric materials (such as TiO_2, Si, and GaN) experience virtually no such absorption losses, thus preserving more photon energy. Due to their extremely low loss, dielectric superlenses can transmit high-frequency information over a wider frequency range, improving resolution and efficiency. This preserves more light intensity, resulting in greater contrast in imaging. Furthermore, metal lenses typically operate effectively only at resonant frequencies. Dielectric superlenses, relying on "geometric phase" or "structural phase" design, are not limited to a single resonant frequency, thus covering a wider range of visible, near-infrared, and mid-infrared wavelengths.

2.4.3 Variable-focus metalens

The basic principle of a variable-focus superlens is to adjust the configuration parameters of the nanostructure units of a two-dimensional metasurface by changing the external environment, causing these microstructures to change and thus adjusting the focal length. Based on the different adjustment mechanisms, they can be roughly divided into three categories. Thermal modulation changes the distribution of nanounits on the super-transparent surface through temperature changes. Electrical modulation generally relies on an external voltage to drive the internal ion distribution of the device to change the phase and thus change the focal length. Mechanical modulation adjusts the focal position and shape by rotating and stretching the metasurface. In general, a variable-focus superlens is a sub-wavelength imaging device with dynamic control capabilities. It also has the ability to clearly amplify sub-wavelength details and adjust the focal length.

3. Case Analysis

The resolution of the superlens is approximately 10-50 nm, far exceeding the 200 nm of traditional lenses and Fresnel diffraction lenses, which is of great help in medical testing, virus analysis, and detection.

3.1 Current Development Status

In traditional microscopes, complex fluorescent labels are required to improve the accuracy of imaging. However, by using superlenses, scientists can study nanostructures without destroying the sample because of their resolution of about 15-50nm. The Joshua Caldwell team at Vanderbilt University proposed using ultra-pure hBN crystals to make superlenses, breaking through the limits of infrared imaging and enabling the observation of bacterial-sized structures on the surface of living cells, with a theoretical resolution of about 30 nm [6]. Superlenses have advantages in observing the microscopic field.

In high-speed optical communications, wavelength division multiplexing and optical signal processing place extremely high demands on component precision. Metalenses can achieve multi-wavelength multiplexing at the nanoscale, increasing communication bandwidth. Furthermore, metalenses incorporating two-dimensional materials such as graphene demonstrate dynamic, adjustable modulation capabilities, paving the way for future 6G communications. Metalenses hold irreplaceable potential in the field of electronic communications.

International companies are highly interested in the commercial potential of metalenses. Google has invested in related startups, seeking to use metalenses in VR/AR headsets; Apple has applied for multiple patents for metalense cameras; and Meta is also researching how to use metalenses to enhance holographic displays. These efforts demonstrate that the application of metalenses is no longer limited to the laboratory but is gradually penetrating the consumer market. Google LLC has invested in metalense-related startups for use in VR/AR devices. Apple Inc. has applied for multiple patents related to metalense cameras, exploring applications in consumer electronics. Meta Platforms is researching the application of metalenses in holographic displays and augmented reality. Metalenses have practical application value in the commercial sector.
Professor Harald Giessen's team has long been researching metalenses, plasmonics, and their applications in biosensing. This includes integrating them with microfluidic chips for real-time monitoring of single-cell environments. This enables real-time monitoring of molecular changes within single-cell environments. This is a practical application of metalenses in the biological field.

3.2 Implications for the Development of Chinese Metalenses

Although China's metalens project started relatively late, it has made rapid progress in recent years. By studying foreign developments in metalens, China can gain many valuable insights.

3.2.1 Equal emphasis on theory and engineering

While developing theories, we should also focus on laboratory construction and promote the virtualization of metasurfaces from static devices to facilitate design and research. In this way, the research cycle of Chinese scientists can be greatly shortened. By combining computer technology with practical experimental technology, for example, Cui Tiejun's team proposed a "coding/digital/programmable metasurface" system to promote metasurfaces from static devices to controllable and reconfigurable devices, laying the foundation for the methodology and device platform for the functionalization and systematization of subsequent metal lenses [2]. This has raised the possibility of China's future intelligent electromagnetic environment and new optical computing platforms.

3.2.2 Empowering China's Strong Enterprises

The development and research of superlenses also has a positive impact on local businesses. In high-speed optical communications, Chinese telecommunications companies can use superlenses to achieve multi-wavelength multiplexing at the nanoscale, increasing communication bandwidth and facilitating the transition from the 5G era to the 6G era. Huawei has applied for a patent for a superlens mobile phone lens. As a high-quality alternative to traditional lenses, superlenses, with their lightness and thinness, demonstrate their commercial importance.

3.2.3 Interdisciplinary collaboration

By leveraging the diverse academic applications of metalenses, China can accelerate development in other areas by integrating them with other research areas and leveraging insights from other countries. For example, to promote the integration of human and machine learning in metalenses, inspired by other countries, China has begun focusing on AI-based learning of the relationship between geometric parameters and optical response. This allows scientists to quickly deduce optical configurations and unit structures based on geometric parameters.

4. Conclusion

The development of traditional optical lenses, Fresnel diffraction lenses, and superlenses is a journey of humanity's continuous breakthroughs in physics and pursuit of ever-higher resolution. Superlenses, which achieve precise control of light waves through artificial microstructures, represent a fundamental innovation in imaging technology. International research is at the forefront of theoretical advancement, interdisciplinary integration, and application exploration, providing valuable experience and inspiration for China. In the future, if China can establish a virtuous cycle between theory, experimentation, and application, promoting interdisciplinary collaboration, the development of human-machine intelligence, and industrialization, research in superlenses will not only bring scientific breakthroughs but also increase the practical value of information technology, life sciences, and industrial manufacturing .
This is a review paper and does not include any specific experiments or experimental data. Future research will include more experiments and experimental data to enhance the credibility of the conclusions.

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