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Metroscopic Imaging and Application Research Based on Polarization-Multiplexed Metalenses

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Abstract. Traditional optical microscope systems are limited by their fundamental drawbacks such as large physical size, limited functions and poor contrast resolution for examining microscopic specimens, but polarization - multiplexed metalenses which represent a significant development in metasurface technology escape from these limits by combining multiple imaging methods into one flat structure through precisely controlling light polarization states with subwavelength nanostructures, and recent research stresses the cooperative work of geometric phase (for example, Pancharatnam - Berry phase) and propagation phase mechanisms making it possible to modulate phase depending on polarization by using hydrogenated amorphous silicon nanoantennas so that controlling the polarization of incoming light allows a single metalens to perform bright - field, edge - enhanced and wide - field imaging simultaneously without any mechanical adjustment, and this research uses a systematic literature review and case study approach to assess the design rules of polarization - multiplexed metalenses and their application in biological imaging and diagnosis, and the results show that polarization multiplexing breaks through the space - bandwidth product restrictions of conventional optical systems creating a compact microscope system with a resolution of 3.91 μm and a field of view of ±40° thus greatly improving the miniaturization and functional flexibility of the system.

Keywords: Polarization, Metalens, Two-dimensional materials, microscopic imaging

1. Introduction

Traditional optical microscopes are crucial tools in biomedical and materials science research but they have considerable drawbacks like large physical size, limited operational capacity and a narrow field of view when set at high - resolution which greatly hinder their use in portable and fast - detection applications; metasurfaces, man - made two - dimensional structures made up of subwavelength resonators, provide a flexible system for accurately controlling wavefronts and metalenses produced by this technology have excellent traits such as being extremely light, very thin and compatible with small - scale systems; for instance, Li et al. [1] managed to combine a metalens array with a Complementary Metal - Oxide - Semiconductor (CMOS) sensor thus creating a chip - sized microscope just 3 – 5 cm in size that could do wide - field imaging, nevertheless, making multifunctional integration remains a big technical challenge.

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Recent research has been focusing more and more on polarization multiplexing techniques which take advantage of how nanostructures respond differently to various polarization states of incident light so as to incorporate multiple functions into flat devices, for example, Professor Jin Peng's team developed a metalens controlled by polarization which could be used for parallel multi - channel polarization imaging and these results showed that metalens structures based on polarization multiplexing offered a feasible route to compact and multi - functional microscopic systems.

Research on metalenses that utilize polarization - multiplexing is at a highly active stage but substantial progress is still needed to tackle fundamental difficulties, mainly aiming to independently and effectively modulate the phase of orthogonal polarization states over wide spectral ranges via the rational design of nano - scale structures which takes advantage of the combined effects of geometric and propagation phase mechanisms enabling the dynamic reconfiguration of optical modes such as bright - field, edge - enhanced, and wide - field imaging on a single integrated system, and although initial studies had shown that such systems were feasible and could perform functions like dual - focus operation or specific imaging tasks there were still several major limitations including low optical conversion efficiency, a narrow operating bandwidth, insufficient achromatic performance, and the lack of standardized fabrication procedures so it was essential to comprehensively reevaluate the basic design principles, the technological path, and future uses of polarization - multiplexed metalenses to get past these obstacles and move the field forward.

This study utilized a combined - methods research framework which integrated a systematic literature review and case study analysis; the method involved comprehensively searching for, critically assessing, and synthesizing key research regarding phase modulation techniques in polarization - multiplexed metalenses, particularly concentrating on their resulting imaging traits, and at the same time, example case studies were closely examined to outline their technical structures, measurable performance figures, and comparative advantages and drawbacks.

2. Design principles and phase modulation mechanisms of polarization-multiplexed metalenses

The basic working principle of polarization - multiplexed metasurfaces lies in their ability to manipulate the polarization state of light by means of subwavelength nanostructures with great precision which made it possible to combine several optical functions into one flat optical component and one main difference from traditional metalenses was that they turned light's polarization from something passive into an active degree of freedom which depended on the coordinated use of two - phase modulation methods: the geometric phase (Pancharatnam - Berry phase) and the propagation phase.

The geometric phase stems from phase jumps brought about by the interaction between circularly polarized light and anisotropic nanostructures; when it strikes a nanostructure which acts like a half - wave plate and is turned at an angle θ, the output light gets an extra geometric phase $\Phi = \pm 2\theta$ with the sign depending on whether the incident light is left - or right - circular, and this phase modulation only relies on the spatial direction of the nanostructure and remains unchanged regardless of the operating wavelength thus allowing for broadband uses, but designs that depend solely on geometric phase are restricted by symmetry limits leading to conjugate phase profiles for left - and right - circular polarizations.

Researchers had to deal with inherent symmetry limitations which made it difficult to manipulate orthogonal polarization states independently so they came up with a propagation phase modulation scheme in which the phase delay that light undergoes when passing through a nanostructure is modulated by systematically changing geometric parameters like length, width, or diameter thus

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changing the effective refractive index and when geometric and propagation phases are cleverly combined in designing individual nano - antennas fully independent and arbitrary phase profiles can be created for orthogonal linear (x - and y -) or circular (left - and right - handed) polarizations for example the research team led by Professor Jin Peng managed to achieve independent phase control for orthogonal linear polarizations by precisely adjusting the major and minor axes of elliptical silicon nitride nano - fins and this design made it possible to have advanced functions such as coaxial confocal and off - axis imaging at two wavelengths (690 nm and 880 nm) [2].

3. Key technological breakthroughs and performance optimization

The transformation of polarization - multiplexed metalenses from theoretical notions to practical uses has been made easier due to substantial progress in multiple key technologies.

3.1. Achromatic design

Chromatic aberration was a major obstacle hindering the early use of metalenses, especially in broadband visible - spectrum imaging, so to reduce this drawback, researchers adopted achromatic design methods combining resonant plans with geometric - phase concepts, and through this means, Li Tao's group cooperating with National Taiwan University created the first achromatic metalens functioning throughout the whole visible spectrum (400 - 660 nm), and after that, to make it more practically useful, the team increased the lens aperture to 1 cm using a multi - order diffractive design based on light - field coherence and structural optimization, which not only made the aperture larger but also extended the achromatic range to 400 - 1100 nm, thus forming a strong foundation for the development of practical flat - optical systems.

3.2. Metalens array and system integration

To alleviate the narrow Field of View (FOV) that is intrinsic to single metalenses and usually restricted to around 30 degrees because of off - axis aberrations, Prof. Li Tao's research team adopted a metalens array setup which allows for the parallel functioning of multiple metalenses with each smaller aperture grabbing a different part of the scene and then these portioned images are computationally combined to form a wide - field composite image thus successfully extending the FOV to 120 degrees while repressing aberrations like coma and distortion; a substantial progress was the chip - level combination of the metalens array with a complementary metal - oxide - semiconductor (CMOS) image sensor resulting in the creation of a chip - scale meta - microscope (MetaScope) having a small size of 3 - 5 cm and this integrated system attains a volume and weight decreased by more than 1000 times in comparison to traditional microscopes at the same time providing a FOV 4 - 7 times greater than that of ordinary commercial microscopes while keeping a resolution of 1.74 μm which effectively avoids the space - bandwidth product limit typical of traditional optical systems [1].

3.3. Polarization multiplexing and dual-focus design

The MetaScope system shows how polarization multiplexing can be implemented via an intricate optical setup and in this method, three different phase patterns are encoded on a single metasurface including a quadratic phase pattern for wide - field imaging, a gradient phase pattern for bright - field imaging and a spiral phase pattern for edge - enhanced imaging; the system has a dual - focus arrangement which allows the focusing of incoming linearly polarized light at a nearby focal point

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(F1) for wide - field imaging while incoming left - or right - circularly polarized light is sent to a farther focal point (F2), with that light being utilized for edge - enhanced and bright - field imaging correspondingly and this setup made it possible to switch instantly among the three imaging modes by adjusting the polarization state of the incoming light without the necessity for mechanical parts.

4. Latest application advances: frontier applications of polarization-multiplexed metalenses in bio-imaging

Polarization - multiplexed metasurface technology has come into being as a remarkable progress in biomedical imaging and Chen et al. [3] designed a dual - polarization channel metasurface which made it possible to get fluorescence and phase - contrast imaging simultaneously on one platform by using elliptical silicon nanopillars to separately modulate x - and y - linearly polarized light so that parallel imaging of cell nucleus fluorescence and cellular morphology through phase contrast at an excitation wavelength of 532 nm could be done and this integrated method offered a new way to observe living cells dynamically [4].

Polarization - multiplexing technology has great merits in the realm of neuroscience and Kim et al. [4] created a metalens that combines geometric and propagation phase profiles for attaining high - resolution polarization imaging of brain tissue sections; this apparatus, functioning at a 635 - nm wavelength, switches between left - and right - handed circularly polarized illumination to get, correspondingly, bright - field and polarization - contrast images of tissue structures which significantly improves the demarcation of neuronal borders and the system reaches an imaging resolution of 2.76 μm, which is higher than that achievable by traditional polarization microscopy methods [3].

The combination of metalenses and computational imaging which was emerging as a revolutionary method has opened up new ways of application and Wang et al. [5] designed a metalens that could be multiplexed in terms of polarization and linked it with a deep - learning framework to create an intelligent microscopic imaging system which made use of convolutional neural networks for reconstructing and enhancing images at a high level thus significantly boosting imaging quality while keeping the system small and experiments showed that this method increased the imaging contrast of unstained breast cancer cells by 3.2 times making it a powerful tool for clinical pathological diagnosis.

5. Realization of multifunctional imaging modes and application validation

Polarization - multiplexed metalenses have a great merit as they can integrate multiple imaging ways onto one small platform thus being a flexible and powerful tool for pushing forward biomedical research.

Bright - field and edge - enhanced imaging has marked a great leap forward in optical metrology and a chromatic confocal sensor, which was jointly developed by researchers from the National University of Defense Technology and Hunan University, attains this by shifting between orthogonal linear polarization states (x - pol and y - pol), and this switching method enables a shift between two working modes, namely a high - precision mode with a measurement scope of 400 μm and an axial precision of ±0.25 μm and a large - range mode having a measurement scope of 1.57 mm and an axial precision of ±1.45 μm [6], and this two - mode function is very useful for applications that need both highly - resolved topographical mapping of concave mirrors and precise thickness evaluation of transparent glass substrates, thus showing great potential for promoting precision measurement technologies.

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A second beneficial characteristic is the capacity for wide - field and large - depth - of - field imaging, and imaging systems founded on metalens arrays intrinsically possess wide - field abilities; for example, the chip - scale microscope created by Professor Li Tao's team showed a field of view measuring 4×4 mm^2 and a depth of field of around 200 μm, and this increased depth of field made it easier to image samples having substantial three - dimensional topography, like cell colonies, as it allowed for the capture of entirely focused images without the necessity for frequently readjusting the focus mechanically, thus significantly improving the efficiency of high - throughput scanning processes.

The third application scenario was about observing biological samples and the MetaScope system managed to image blood cells successfully; when in the edge - enhanced imaging mode, the boundaries of cells could be clearly defined which is an important characteristic for boosting contrast during the visualization of transparent samples like unstained cells and at the same time, the wide - field imaging mode made it possible to quickly locate and statistically analyze the distribution of cells over large sample areas so all these applications showed that this technology had practical uses in fields such as pathological diagnosis and cellular research.

6. Technical challenges and future perspectives

The extensive application of polarization - multiplexed metalenses has been constantly encountering substantial difficulties; first of all, the diffraction efficiency throughout the entire visible spectrum has remained less than ideal which is currently the main emphasis of research; second, large - scale nanofabrication is plagued by crucial restrictions on uniformity and reproducibility which are major manufacturing obstacles that negatively impact image quality and production output; moreover, although achromatic designs have widened the operational bandwidth, the performance at the edges of the spectral band could be further optimized.

The future course of this technology was marked by progress in dynamic adjustability and deep combination with artificial intelligence and a crucial research path entailed integrating metalenses with liquid crystals which made it possible to dynamically adjust the focal length or function by applying an external electric field and at the same time using metalenses as the front - end for optical computation to process optical information directly along with AI algorithms for image reconstruction and analysis offered a hopeful way to develop smart computational imaging systems that could overcome the built - in limitations of traditional optics as Prof. Li Tao's team had envisaged and meta - photonic technology was set to transform tools for life sciences research and medical diagnosis.

7. Conclusion

This research methodically expounded on the design tenets, crucial technological innovations, and various applications of polarization - multiplexed metalenses in microscopic imaging and by means of the collaborative combination of geometric and propagation phases at the subwavelength level, this technique effectively transformed polarization states into a dynamic control variable which made it possible to integrate multiple functions like bright - field, edge - enhanced, and wide - field imaging within one flat device and significant progress, such as aberration - free design, the integration of metalens arrays, and dual - focus arrangements, had dealt with important restrictions of traditional optics especially the limitation regarding the space - bandwidth product thus allowing for the creation of extremely compact, high - performance microscopic systems.

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There have been significant difficulties in boosting diffraction effectiveness, widening the operational frequency range, and normalizing large - scale nanofabrication procedures for metalenses and future research was supposed to give priority to the development of metalenses that could be dynamically adjusted perhaps by integrating them with liquid crystals or Micro - Electromechanical Systems (MEMS) so as to achieve active functional control and moreover the deep combination of metalenses with computational imaging and artificial intelligence algorithms offered a great chance for creating intelligent, next - generation imaging platforms and as these technological progressions grew more advanced polarization - multiplexed metalenses were anticipated to transform applications in portable diagnostics, high - throughput bio - sensing, and real - time life - science research finally setting up a new pattern in miniaturized optical technology.

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