Opto-Electronic Advances

Editorial

May 2024, Vol. 7, No. 5

DOI: 10.29026/oea.2024.240134

Special issue: Catenary optics and catenary electromagnetics

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Sun Q, Hong MH. Special issue: Catenary optics and catenary electromagnetics. *Opto-Electron Adv* **7**, 240134 (2024).

As a natural mathematical form, a catenary is the curve that a hanging chain or cable adopts under its own weight when supported at its ends in a homogeneous gravitational field. This unique shape arises from the balance of forces acting on each segment of the chain, resulting in a curve described by hyperbolic cosine functions. Catenary functions play pivotal roles in describing the electromagnetic field, intensity distribution, and dispersion of structured light on the sub-wavelength scale[1]. The hyperbolic cosine catenary function is a special solution of the wave function, while recent researches have found that the dispersion curves of capacitive metasurfaces exhibit the characteristics of the catenary of equal strength, providing a mathematical and physical model to predict the electromagnetic properties of functional metasurfaces[2]. Moreover, catenary structures (the catenary of equal phase gradient) can be used as a fundamental building block of metasurfaces. Due to the quasi-continuous phase modulation mechanism, the catenary structures can suppress the phase sampling errors associated with traditional discrete structures, achieving higher efficiency and broader bandwidth. Due to the unique optical properties, catenary optics and catenary electromagnetics have been widely applied in the fields of lithography[3], absorbers[4], antennas[5,6], and imaging[7].

To highlight the importance and impact of the most significant breakthroughs in the cutting-edge catenary optics and electromagnetics, a special issue has been organized in the journal *Opto-Electronic Advances*. This special issue includes 4 excellent original articles on the topic of catenary optics. These contents cover the general design and optimization of quasi-continuous structures, as well as the applications of catenary optical fields in strong coupling and high-order harmonic generation.

The design of quasi-continuous nanostrips

Metasurfaces and metalenses have been widely applied in various multifunctional lenses in recent years, due to their excellent abilities to manipulate the wavefront of light[8,9]. However, many metalenses are composed of discrete structures, leading to the issues of phase sampling insufficiency and undesired coupling among adjacent structures. The streamlined metasurface composed of catenary-like structures provides a way to solve this issue[7]. However, the operational wavelength is in the infrared range. Their abilities in engineering phase and amplitude also need to be enhanced.

To address this issue, Zhang et al. designed a dielectric metasurface composed of quasi-continuous nanostrips[10], which can achieve broadband and high-efficiency metalenses for visible and near infra-red wavelengths (450–1000 nm). The phase realized by these quasi-con-

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Received: 5 June 2024; Accepted: 6 June 2024; Published online: 7 June 2024

tinuous nanostrips is almost continuous in space, except for a few phase jump points. Additionally, based on the geometric phase principle, which is related to the different orientation angles of the nanostrips at different spatial positions, the designed quasi-continuous metalenses exhibit achromatic performance. As a verification, the metalens composed of the quasi-continuous nanostrips are designed and measured. Within the wavelength range of 500 to 1000 nm, the metalens achieved an average efficiency of 54.24%, significantly higher than the previously reported metalenses composed of the discrete structures of the same thickness. A superoscillatory lens is designed and fabricated with a focal spot 0.7 times of the diffraction limit. This work provides a general framework to design complex quasi-continuous meta-optics.

Towards the efficiency limit of catenary meta-optics

Due to the broadband and high-efficiency characteristics, catenary structures have been widely applied in various fields[11,12]. Generally, the phase shift generated by the catenary structures is purely geometric phases. However, the inconsistent filling ration of local catenary structures may lead to an undesired parasitic propagation phase, leading to the low efficiency of catenary meta-optics[7]. In the previous researches, an isophase streamline optimization method is proposed to increase the efficiency of catenary structures[7]. However, driven by periodic boundary approximation, such an optimization method faces the challenge of inaccurate electromagnetic field calculation, making it difficult to optimize the efficiency of the catenary meta-optics.

To approach the performance limits of the catenary meta-optics, Chen et al. proposed a field-driven optimization (FDO) algorithm, in which the real boundary conditions are utilized to calculate the electromagnetic waves[13]. Unlike the traditional shape optimization algorithms, such an algorithm uses the local width at each point on the catenary as the optimization target, enabling precise control over both the geometric and propagation phases of the structures. The FDO method has the benefit of low parameterization cost, requiring only a few parameters to describe the structures. Within 30 iterations, the efficiency of the catenary is optimized to over 99%, achieving near-perfect wavefront control. Additionally, this work extends the applications of catenary structures to arbitrary polarizations for the first time. By combining forward design with the FDO, the quasi-continuous meta-optics can be designed for arbitrary polarized incidence. Moreover, based on the FDO method, a library composed of shape-optimized catenary structures is designed. Rapid design of centimeter-scale meta-optics with high efficiency can be achieved using this library. The FDO method can be extended to design and optimize 2D metalenses. Simulations and experiments show that the performance of the catenary meta-optics designed based on the library is improved by ~15% compared to the equal-width catenary-like structures. This work further enhances the performance of the catenary meta-optics and may further promote the development of the catenary optics.

Strong coupling and catenary field enhancement

Strong coupling can be achieved when the energy exchange rates among the subsystems surpass the decay rates of plasmons and excitons, which is crucial in developing nanophotonic devices that exceed the speed of semiconductor electronics and overcome the size limitations of photonic dielectrics[14]. The coupling can be increased by decreasing the effective cavity volume of the plasmonic nanocavities. However, to achieve strong coupling in molecular excitons, a substantial number of organic molecules must be included. Additionally, controlling the electric field confinement around the plasmonic cavity remains a challenge[15]. Two-dimensional transition metal dichalcogenides (TMDCs) are excellent candidates in observing plasmon-exciton coupling. The plasmonic modes of single nanoparticles demonstrated a strong coupling criterion with TMDCs as exciton modes. However, the challenges, such as the irreversibility of plasmonic scanning methods and unsuitability for integrating complex systems, persist.

To address these issues, Andergachew et al. investigated a strong coupling of surface plasmons on metallic metamaterial nanocavities with excitons on TMDC monolayers for the first time[16]. The introduced plasmonic metamaterial nanocavity (Au/Ag cavity), which exhibits catenary-shaped optical fields, is introduced by transforming surface plasmon polaritons (SPP) with strong near-field enhancement. By coupling surface plasmons in the cavity, the catenary-shaped optical fields in metal-dielectric-metal (MIM) structures can be formed, with strength strongly dependent on the cavity's gap. Therefore, controlling the gap in the metallic metamaterial/nanoantennas is crucial in enhancing light-matter interactions. As validations, the Au cavity is utilized as the plasmon mode, while $MoSe_2$ and WSe_2 serve as the exciton modes. The plexciton energies can be realized by varying the cavity gap and the thickness of the gold nanostructures. As a result, based on highly localized field enhancement in the near field of Au cavity, a large Rabi splitting ranging from 77.86 to 320 meV is achieved by Au-$MoSe_2$ and Au-WSe_2 heterostructures. The plasmonic Au cavity has a quality factor of ~35, with its heterostructures potentially enabling a single-photon emitter. This work would promote the development of optoelectronic devices, optical switching, and sensing.

Resonantly enhanced second- and third-harmonic generation

Metasurfaces are crucial platforms for nonlinear optics due to their abilities to enhance and confine localized optical fields. Recent researches show that high quality Q factor resonant effects can be achieved via optically resonant all-dielectric metasurfaces based on guided mode resonances (GMRs)[17]. The underlying physics of the collective phenomenon of GMRs in metasurfaces with a periodic lattice can be explained by the propagation of in-plane diffractive modes under the condition of total internal reflection. However, these diffraction modes can couple to the radiation continuum, allowing optical energy to leak into free space. The generation of bound states in the continuum (BICs) provides a novel method to achieve a strong coupling between light and certain photonic systems[18,19]. However, in practice, the Q factor of BICs is limited due to surface roughness, material loss, inherent manufacturing defect, and perturbation. Dielectric metasurfaces that break in-plane inversion symmetry can achieve sharp resonances with extremely high Q factors at high symmetry points (such as the Γ point) through symmetry-protected BICs[20].

Wang et al. proposed an amorphous silicon nonlinear metasurface that enhances and tailors the second- and third-order nonlinear optical responses of the metasurface utilizing the versatile physics of both GMRs and symmetry-protected BICs[21]. The enhancement of nonlinear optical effects from asymmetric metasurfaces is compared in terms of their distinct physical mechanisms. In addition, different from other studies that focused mostly on one particular harmonic order, the proposed work shows a large enhancement of both the second-harmonic generation (550 times enhancement) and third-harmonic generation (5000-fold enhancement) from the same amorphous silicon metasurface. Moreover, numerical examination reveals the asymmetry dependence of the second- and third-harmonic generation in centrosymmetric amorphous silicon. This work could facilitate innovative photonic applications and fabricate devices with enhanced or new functionalities.

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Competing interests

The authors declare no competing financial interests.

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