Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA27987

Design and Application of Metasurface-Enabled Light Harvesting Technology

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Abstract. Optical metasurfaces, with their advantages of miniaturization and integration as well as their outstanding ability to manipulate light fields, have been deeply applied in the research of light harvesting technology in recent years, marking a new stage of development in this interdisciplinary field. Recent studies have demonstrated several effective design strategies. Periodic nanostructures can excite plasmonic, Fabry-Pérot, and Mie resonances, enabling broadband and angle-insensitive absorption. Symmetry engineering transforms bound states in the continuum (BICs) into quasi-BICs with ultrahigh Q resonances, producing strong field confinement that is valuable for sensing and filtering. Multipolar coupling further enhances performance by exploiting the interaction between bright and dark modes, which suppresses radiative loss and sharpens spectral features. These approaches have led to significant progress in applications. In energy harvesting, metasurface absorbers and selective emitters improve solar utilization and thermophotovoltaic efficiency while maintaining thermal stability. In sensing and detection, enhanced near fields enable trace-level molecular detection and concentration quantification. In terahertz communication, tunable metasurfaces allow ultrafast modulation, frequency switching, and adaptive beam steering, providing compact solutions for next-generation wireless systems. These designs and applications will pave the way for future development and opportunities of metasurface-based light harvesting technology.

Keywords: Metasurfaces, energy conversion, light harvesting, optical responses

1. Introduction

Light harvesting refers to the efficient absorption and utilization of incident photons by tailoring the interaction between light and matter. It is central to a wide spectrum of technologies, ranging from solar energy conversion and photodetection to thermal emission engineering and biosensing. Conventional light harvesting techniques often rely on random scattering structures, multilayer coatings, or bulky optical elements to enhance absorption and trapping. While these approaches have been somewhat successful, they are constrained by the diffraction limit, narrowband operation, and large device volumes. In addition, their lack of tunability and limited compatibility with on-chip integration restrict further application. These challenges underscore the need for novel photonic platforms that can provide compact geometries, versatile optical responses, and efficient light-matter coupling.

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DOI: 10.54254/2755-2721/2026.KA27987

Optical metasurfaces, composed of two-dimensional arrays of subwavelength artificial structures, offer a revolutionary alternative [1]. By engineering the geometry, size and arrangement of their building blocks, metasurfaces can achieve unprecedented control over the amplitude, phase, polarization, and spectral properties of light within an ultrathin thickness [1-3]. Their operating principles rely on diverse physical mechanisms, including plasmonic resonances in metallic nanostructures, Mie resonances in high-index dielectric particles, guided-mode resonances in planar waveguides, and bound states in the continuum (BICs). These mechanisms enable functionalities such as broadband absorption, strong near-field localization, enhanced nonlinear responses, and dynamically tunable spectra [4, 5]. Compared with traditional optical components, metasurfaces combine compactness, multifunctionality, and compatibility with large-scale nanofabrication, making them an ideal platform for next-generation light harvesting devices.

This review highlights recent progress in metasurface-enabled light harvesting, focusing on key design strategies such as periodic arrays, multipolar coupling, and symmetry breaking. Then it further discusses applications in broadband solar absorption, high-sensitivity biosensing, and reconfigurable terahertz communication, aiming to outline both current advantages and future challenges.

2. Designing concept of metasurface-based light-harvesting devices

2.1. Conventional periodic microstructure array

Conventional periodic microstructured metasurfaces enable broadband and high-efficiency light trapping by combining localized surface plasmon resonances (SPR) with Fabry-Pérot (F-P) cavity modes. In Ti-based multilayer metal-dielectric-metal architectures incorporating upconversion nanoparticles (UCNP) studied by Wen et al., the SPR of Ti nanostructures dominates short wavelength absorption while interlayer F-P cavities enhance the near-infrared region, producing over 95% absorption from 540 to 1600 nm and near-unity peaks at 549 nm and 808 nm [6]. The latter aligns with Nd3+/Yb3+-doped UCNP excitation bands, enabling efficient NIR-to-visible upconversion.

TiN cylindrical arrays, consisting of a TiN substrate, dielectric spacer, and periodic nanopillars, achieve average solar absorptance of 0.94 across 300-2500 nm, with SPR-driven visible absorption and cavity-enhanced infrared response, according to the research of Yang et al. [7]. A related TiN/Al2O3/TiN configuration with a top refractory nanostructure yields over 91% average absorption in the same spectral range, offering material and geometry versatility, high-temperature stability, tolerance to fabrication deviations, and angular robustness [8].

In parallel, graphene nanodisk arrays with asymmetric size distribution support two independent electric-dipole resonances in the mid-infrared to terahertz range, where Fermi level tuning via electrostatic gating or chemical doping enables large spectral shifts and local field enhancement factors above 10^3, providing a reconfigurable platform for sensing, modulation, and non-linear optics, researched by Fan et al [9].

To sum up, by adjusting the parameters of the periodic array, multiple resonant modes are stimulated. Thus, broadband absorption spectrum and peak can be realized. The materials used also have an impact on the absorption spectrum and give rise to properties like upconversion and high-temperature stability.

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2.2. Design based on symmetry breaking

Symmetry-breaking strategies in dielectric metasurfaces convert symmetry-protected BICs into high-Q quasi-BICs by introducing controlled perturbations that open radiative channels while preserving strong field confinement. In a $Ge_2Sb_2Se_4Te$ (GSST) metasurface composed of three parallel nanobars per unit cell studied by Huang et al., lateral displacement of the central nanobar by a distance d breaks mirror symmetry, exciting a magnetic-dipole-dominated quasi-BIC with $Q \propto d^{-2}$ and average field enhancement factors exceeding 10^4 [10]. The phase-change capability of GSST allows active control of resonance sharpness and intensity. Partial crystallization increases optical loss, broadens the linewidth, and reduces enhancement, with modulation efficiencies approaching 100% [10].

Another realization employs a free-standing silicon membrane patterned with a square lattice of air holes, where periodic radius perturbations Δr implement Brillouin zone folding, mapping guided modes to the Γ point and enabling free-space coupling, according to the research of Adi et al. [11]. This design supports TE and TM quasi-BICs with measured Q factors up to 722, field enhancements around 38, and high refractive index sensitivities of 1500 nm/RIU [11]. The open cavity geometry ensures direct near-field access, enabling vibrational strong coupling with molecular resonances, as demonstrated by Rabi splitting up to 20 cm^{-1} in PMMA, surpassing the strong coupling threshold [11].

In both platforms, precise control of the asymmetry parameter balances radiative leakage and confinement, enabling tailored performance for active modulation, strong coupling, and enhanced light-matter interaction.

2.3. Design based on multipolar resonant coupling

Multipolar resonance coupling exploits the interaction between low-order and high-order Mie modes in periodic arrays of high-index dielectric resonators. While high-order modes such as electric octupoles exhibit weak direct coupling to normally incident plane waves, their excitation can be mediated through lattice-induced far-field coupling with bright dipole modes. When the scattered fields from neighboring resonators satisfy an amplitude and phase matching condition, the bright dipole response is suppressed via destructive interference, and energy is trapped in the dark high-order mode, forming a narrowband quasi-trapped state with enhanced field confinement. This effect requires matching the modal parity for efficient coupling, operating in the sub-diffractive regime to suppress radiative leakage, and using low-loss materials to preserve high Q factors.

In the studied disk-array platform, an isolated resonator supports a narrow electric octupole mode alongside a broad electric dipole mode [12]. When arranged in a two-dimensional lattice with optimized period, the dipole mode excites the octupole via far-field lattice coupling, producing a sharp reflectance dip and strong in-plane field localization at the octupole resonance. Numerical and analytical multipole-lattice models confirm that only modes with compatible parity can couple efficiently, and that substrate refractive index significantly affects the phase conditions and Q factor. The resulting trapped state exhibits high Q with strong energy storage and is robust against small period variations, though sensitive to particle geometry and material loss.

This symmetry-preserving approach offers a route to high-Q narrowband resonances without breaking unit cell geometry, enabling applications in sensing, nonlinear optics, low-threshold nanolasers, and directional emission control.

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3. Applications of metasurface-based light-harvesting technology

3.1. Efficient light energy conversion

Metasurface-based absorbers have shown significant potential for high-efficiency solar energy harvesting and selective thermal emission due to their ability to engineer spectral absorption profiles with subwavelength precision. A representative example is the ultra-broadband Ti-based metamaterial absorber composed of a Ti-SiO_2-a-Si periodic square array atop an a-Si spacer and Ti substrate [13]. By leveraging the combined effects of surface plasmon polaritons (SPPs), Fabry-Pérot (F-P) cavity modes, Mie resonances, and electric dipole resonances (EDRs), the device achieves over 90% absorption from 329 to 1905 nm with an average absorptance of 95.6% across 300-2000 nm [13]. The design is polarization-insensitive, maintains high absorption for incident angles up to large obliquities, and uses refractory Ti for cost-effectiveness, mechanical robustness, and high-temperature stability. Its absorption spectrum aligns closely with the solar spectrum, enabling efficient photothermal conversion and applicability in solar cells, thermal emitters, and concentrated solar power systems.

Beyond broadband capture, optical metasurfaces can be tailored for spectrally selective absorption to optimize energy conversion efficiency in thermophotovoltaics (TPV) and radiative cooling [14]. By exploiting guided-mode resonances, multipolar interference, and material dispersion engineering, such designs can produce narrowband, high-emissivity peaks matched to photovoltaic band gaps while suppressing out-of-band thermal emission, thereby maximizing usable photon flux and reducing entropy losses. Structural tunability, including lattice period, element geometry, and high-index dielectric integration, allows for tailoring the thermal emission spectrum under high-temperature operation. These metasurface emitters can also be designed to provide angular control of emission, further enhancing the directional and spectral matching between the emitter and the photovoltaic cell, which is crucial for achieving high TPV conversion efficiencies.

Metasurface-enabled light harvesting technology is widely applied in efficient light energy conversion. It provides solutions for not only broadband but also spectrally tunable and selective devices, paving the way for further application of metasurface-based photonic systems.

3.2. Ultra-fine detection and sensing

Metasurfaces offer unique advantages for ultra-sensitive detection and sensing due to their ability to engineer resonances with strong field confinement, high Q factors, and tailored spectral positions. In biosensing, metasurfaces can enhance fluorescence, Raman, or infrared vibrational signals by orders of magnitude, thereby lowering the limit of detection and enabling rapid, label-free analysis [15]. Fluorescence-enhancing platforms, surface-enhanced infrared absorption (SEIRA), and guided mode or BIC resonances have been employed to improve sensitivity and specificity, with additional benefits of compactness and CMOS-compatible fabrication.

A notable example is a hybrid mid-infrared metasurface biosensor that simultaneously achieves sensitive quantification and molecular identification of proteins [16]. The device consists of gold nanorod antenna arrays above a metallic mirror separated by a thin dielectric spacer, forming nanogaps that generate intense near fields. Adsorption of protein monolayers produces measurable plasmon resonance shifts for quantification, while tuning the resonance to overlap vibrational fingerprint bands yields greatly enhanced infrared absorption for molecular identification and secondary structure analysis. This dual-function approach achieves detection limits in the picomolar

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range while maintaining spectral selectivity, and the inclusion of tunable elements such as graphene gating allows dynamic matching to target molecular features.

Metasurface sensing principles extend beyond biochemical detection to compact, integrated spectroscopic systems. A recent mid-infrared metasurface microspectrometer integrates a lithographically defined filter array with a thermal detector and machine-learning classification for gas detection [17]. The filter array samples the incident spectrum in discrete bands between 6 and 14 μm without moving parts, and thermal stabilization minimizes drift for reliable measurements. The system identifies gases such as CO_2, CH_4, NH_3, and MEK with near-unity classification accuracy, demonstrating that metasurface-enabled spectral sampling combined with computational analysis can yield portable, low-cost, and highly specific environmental and industrial sensing solutions.

With the local field enhancement characteristic and multiple resonant modes that can be stimulated, metasurface-based devices have been applied in material identification like protein structure determination and gas sensing. With the development of relevant technology, more integrated and intelligent metasurface-based systems will be created.

3.3. Terahertz communication technology

Metasurface-based terahertz (THz) communication devices have been developed to enable ultra-fast signal processing, tunable spectral control, and agile beam steering for future high-capacity wireless links. Graphene-based metamaterials exploit strong intraband absorption and the extremely small electronic heat capacity of massless carriers to achieve sub-nanosecond THz-to-visible light conversion [18]. In such devices, intense THz pulses rapidly heat the electron gas, and the resulting broadband thermal emission in the visible/near-infrared can be modulated by electrostatic gating. Incorporating a grating-type metamaterial enhances the emitted power by two orders of magnitude. A thermodynamic model balancing THz absorption and carrier heat capacity accurately describes the gate-dependent electron temperature and emission spectra, indicating the potential for compact, high-speed THz-to-optical transducers in ultrafast communication systems.

Hybrid active metasurfaces integrating photo-responsive 2D semiconductors with resonant photonic structures enable dynamic control of THz absorption spectra [19]. For example, $MoTe_2$ layers coupled to split-ring resonators support dual-band perfect absorption in the unpumped state (e.g., at 0.456 and 0.624 THz) [19]. Optical excitation modifies the carrier conductivity of $MoTe_2$, described by a Drude-Smith model, which shifts the resonance profile into a single peak near 0.55 THz [19]. This transition is reversible and exhibits large modulation depths, offering a compact approach to tunable THz filters, modulators, and frequency-selective absorbers suitable for adaptive communication and sensing.

Electronically programmable THz metasurfaces provide real-time, reconfigurable wavefront control for beam steering and spatial multiplexing [20]. Arrays of subwavelength meta-elements incorporating GaN/AlGaN high-electron-mobility transistors enable 1-bit phase modulation with 180◦ phase contrast at 0.34 THz, supporting multi-beam generation, diffuse scattering, and wide-angle beam steering with degree-level precision [20]. Columnar addressing allows independent control of subarrays, and demonstrated switching speeds reach 100 MHz, with prospects toward GHz operation in optimized platforms [20]. These capabilities are critical for dynamic beam-forming, user tracking, and channel reconfiguration in next-generation THz communication networks.

Metasurface-based THz communication devices have enabled ultra-fast signal processing, tunable spectral control, and agile beam steering for high-capacity wireless links. These

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4. Challenge and outlook

Despite these significant achievements, critical challenges persist in bringing metasurface technologies to practical fruition. Fabrication scalability remains a pressing concern, as the transition from laboratory-scale demonstrations to mass production requires cost-effective and high-throughput nanomanufacturing techniques [1,2]. Material stability under operational conditions, particularly for plasmonic structures susceptible to oxidation and thermal degradation, must be addressed to ensure long-term reliability. Additionally, the inherent complexity of multi-physics design optimization poses substantial computational demands, necessitating more efficient algorithms and interdisciplinary approaches to streamline the development cycle [5].

Looking to the future, the convergence of metasurface technology with cutting-edge disciplines promises to unlock new frontiers in light harvesting. Dynamic metasystems incorporating phase-change materials or electro-optic effects could enable real-time adaptive control of optical responses [19], while the exploration of topological photonic states may reveal novel mechanisms for robust light trapping [1, 2, 5]. The integration of machine learning techniques is poised to accelerate the discovery of optimal metasurface architectures, potentially uncovering designs that defy conventional intuition. As these innovations mature, they will pave the way for metasurfaces to transcend their current niche applications, becoming ubiquitous components in next-generation renewable energy systems, ultra-compact photonic circuits, and advanced sensing platforms. The continued synergy between fundamental research and engineering innovation will be paramount in realizing the full potential of metasurface-based light harvesting, ultimately contributing to solutions for global challenges in energy sustainability and information technologies [14, 17].

5. Conclusions

This review elucidates the remarkable progress in metasurface-enabled light harvesting technologies, and discusses the possible challenges and outlook for future development. It showcases their unparalleled ability to manipulate light at the subwavelength scale through innovative design paradigms.

By using multi-resonance coupling and symmetry engineering, metasurfaces have overcome fundamental limitations of conventional optics, enabling tailored light-matter interactions with exceptional precision. These advancements have catalyzed transformative applications across diverse domains, including ultra-broadband solar energy conversion, where metasurfaces enhance absorption while minimizing reflection losses, high-sensitivity biosensing platforms that leverage localized field enhancement for single-molecule detection, and advanced light extraction systems that boost the efficiency of optoelectronic devices. The integration of these designs with emerging computational tools has further expanded the horizons of what can be achieved in nanophotonic light harvesting.

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