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A long wave cutoff perfect absorber with a nanocone array structure

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INTRODUCTION & AIM

Metamaterials have revolutionized electromagnetic wave manipulation, enabling groundbreaking devices such as metalenses, invisibility cloaks, and high-performance absorbers. Their supernatural physical behaviors, including programmable forms and adjustable electromagnetic responses, provide a foundation for advanced optical engineering.

Amidst the escalating global energy crisis, the efficient harvesting of solar energy has become a top priority for sustainable development. Solar energy utilization requires sophisticated devices capable of precise spectral control to maximize heat conversion while minimizing losses.

Ideal solar heat absorbers must possess a specific "cut-off" characteristic: high absorption across the ultraviolet (UV) to near-infrared (NIR) spectrum to capture maximum solar energy, paired with near-zero absorption (and low emittance) at longer wavelengths. This selectivity is crucial to prevent the re-radiation of energy, which typically occurs at near-infrared and mid-infrared thermal wavelengths.

While previous works have achieved high average absorption (e.g., above 92% or 91%), maintaining a sharp transition between the absorption and non-absorption bands remains a significant challenge in sub-wavelength structure design.

This study proposes and numerically demonstrates a Long Wave Cutoff Perfect Absorber (LWCPA) based on a multi-layer nanocone array. By nesting stacked layers of Si_3N_4, Cr, and Au within an InP nanocone, this research aims to:

- Achieve near-perfect absorption (>97%) in the solar spectrum.
- Establish an extremely sharp cut-off slope to suppress thermal re-radiation.
- Provide a robust and scalable design for next-generation solar thermal photoelectric and renewable energy applications.

METHOD

- The unit cell consists of an InP nanocone grown on a SiO_2 substrate. Nested inside the InP cone are stacked layers of Si_3N_4, Cr, and an Au cone.
- The Finite Difference Time Domain (FDTD) method was used for design and optimization.
- Optimized dimensions include P = 300 nm, a_1 = 184 nm, a_2 = 65 nm, a_3 = 36 nm, h_1 = 70 nm, h_2 = 250 nm, h_3 = 117 nm, h_4 = 590 nm.
- Periodic boundary conditions were applied to x and y axes, with a perfectly matched layer (PML) on the z axis.

RESULTS & DISCUSSION

- The Long Wave Cutoff Perfect Absorber achieves 97.9% average absorption (200–820 nm).
- Absorption drops from 95% at 820 nm to 10% at 1880 nm, with only 3.5% absorption in the 1880–4000 nm band.
- The design exhibits an Extinction Ratio (ER) of 9.78 dB, an Extinction Difference (ED) of 85%, and a Cut-off Slope (CS) of 0.234 nm^{-1}.
- Analysis of parameters like period P = 300 nm and height h_4 = 590 nm confirms the design maintains high performance within standard manufacturing tolerances.

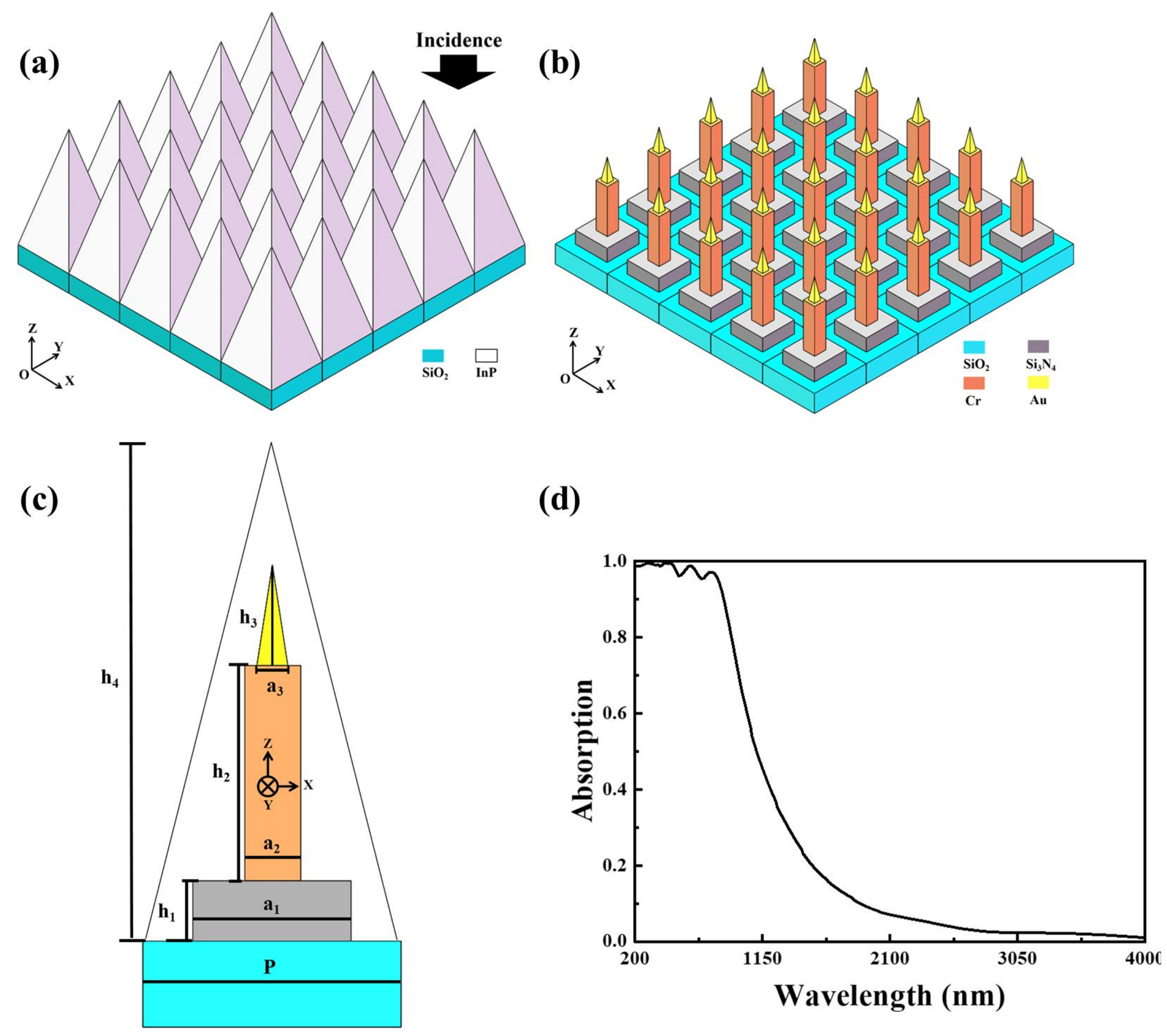

Figure 1. (a) External structure of the LWCPA (5×5 array) with incident light along -Z direction; (b) Internal structure of the 5×5 nanocone array; (c) Unit cell cross-section along the X-axis; (d) Theoretical absorption spectrum from 200 nm to 4000 nm.

CONCLUSION

A nanocone-based LWCPA has been successfully developed, integrating inorganic compounds (Si_3N_4), metals (Cr, Au), and semiconductors (InP). The device exhibits superior spectral selectivity, positioning it as a promising candidate for renewable energy technologies, particularly in solar thermal energy systems.

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