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[Invited] Plasmonic color filters for multi-spectral imaging

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Abstract We applied plasmonics to a Si CMOS image sensor for both color filtering and near-infrared (NIR) sensitivity enhancement. A plasmonic color filter, based on periodic metal nano-gratings with concentric corrugations, allows simultaneous visible and NIR imaging without external filters. Additionally, plasmonic diffraction with deep trench isolation (DTI) dramatically improved NIR absorption, achieving an 8.2-fold enhancement. This integrated approach offers a compact, CMOS-compatible solution for advanced multispectral imaging applications.

Keywords: color filters, metal thin film, surface plasmon resonance, near-infrared

1. Introduction

The application of surface plasmon resonance (SPR) has been explored in various fields, including surface-enhanced Raman scattering, fluorescence enhancement, and photovoltaics. Traditional plasmonics focuses on using the electric field enhancement on metal surfaces. Our group has extended this concept to image sensors, particularly in color filtering and near-infrared (NIR) sensitivity enhancement [1-5].

2. Plasmonic color filters from VIS to NIR

We developed an on-chip color filter using periodic metallic nano-gratings surrounding a single aperture for multispectral imaging from visible to near-infrared (NIR) wavelengths. Our developed plasmonic color filter for visible to NIR multispectral imaging introduces significant improvements over conventional color filters. Traditional image sensors rely on organic color filters, which often suffer from unwanted secondary transmission in the NIR region. To address this, external infrared cut filters are typically added to prevent NIR light from reaching the sensor. However, this setup requires additional image processing systems or multispectral filter arrays to handle both RGB and NIR light simultaneously, increasing system complexity and size. In contrast, our approach employs plasmonic color filters integrated directly onto the image sensor, eliminating the need for external infrared cut filters. These filters use periodic metallic nano-gratings surrounding a sub-wavelength single aperture to control light transmission across the visible and NIR spectrum. Each color in the RGB-NIR range can be selected by adjusting the period of the concentric corrugations in the metal film, allowing for simultaneous capture of visible and NIR information. This capability enables several advanced imaging applications. For example, NIR pulses can be used in time-of-flight range imaging to obtain depth information, while visible light provides detailed texture and color. In biomedical imaging, the deep tissue penetration of NIR light can be exploited to detect the absorption characteristics of biomolecules within the NIR window, supporting non-invasive diagnostic methods. In vehicle-mounted cameras and security systems, the ability to simultaneously capture visible and NIR light enhances image recognition, particularly in low-light conditions, and reduces the overall system size by integrating multiple functionalities into a single sensor. Our plasmonic filter design employed a silver film with concentric, periodic corrugations, capable of multi-band color filtering from the visible to NIR range (Fig. 1). Spectral measurements show that each filter exhibited a narrow Gaussian transmission band, with peak wavelengths corresponding to blue, green, yellow, and red. These filters have a full-width at half-maximum (FWHM) of around 100 nm, significantly narrower than conventional plasmonic color filters based on metallic hole arrays, which results in more precise color selection.

Additionally, the filter's peak transmission shifted from the visible to the NIR region as the corrugation period increased. This shift is a direct consequence of the surface plasmon resonance (SPR) conditions, which depends on the periodic corrugations. Our plasmonic color filters offer not only high wavelength selectivity and simultaneous visible-NIR imaging but also reduced system size and improved optical performance compared to traditional methods. These filters can be especially beneficial for compact, high-performance imaging systems used in applications like security cameras, autonomous vehicles, and medical diagnostics.

3. Plasmonic grating for NIR sensitivity enhancement

To enhance near-infrared (NIR) sensitivity in silicon-based image sensors, we introduced an innovative approach that combined plasmonic diffraction with deep trench isolation (DTI) technology (Fig. 2). Traditional silicon sensors typically exhibit poor NIR sensitivity due to the low absorption coefficient of silicon in this spectral region. While increasing the thickness of the silicon layer can improve NIR sensitivity, this leads to challenges such as pixel crosstalk and difficulties in implementing DTI with high aspect ratio. Our solution leverages

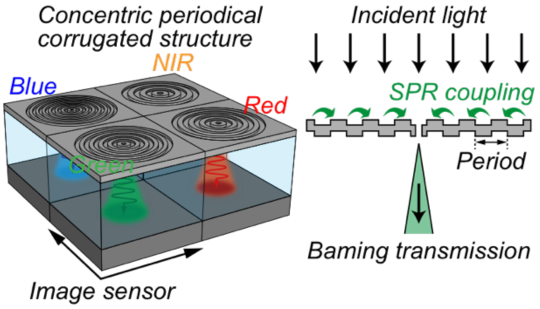

Fig. 1 Schematic diagram of plasmonic color filter with concentric periodic corrugation for VIS and NIR imaging.

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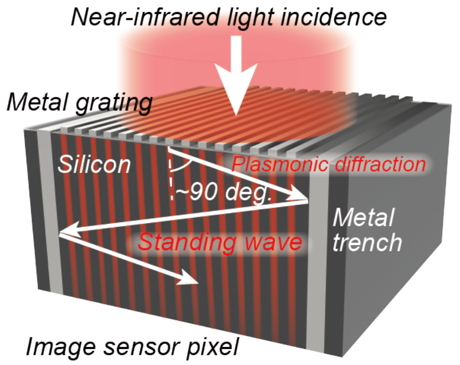

Fig. 2 Schematic diagram of plasmonic diffraction with DTI for NIR sensitivity enhancement.

quasi-resonance of surface plasmon and diffraction mechanisms to enhance NIR absorption efficiency without increasing the silicon thickness.In our CMOS image sensor design, we utilized metallic nano-gratings which grating period was slightly shifted from the resonant condition, the diffracted light was directed into the silicon substrate, rather than propagating along the metal surface in resonance. The diffracted light approached a near-90-degree angle and was repeatedly reflected by the DTI. The multiple reflection process extended the effective optical path length within the silicon, thereby enhancing overall NIR absorption. In our design, silver gratings with a period of 265 nm, a width of 230 nm, and a height of 85 nm were employed to achieve a high diffraction angle of approximately 80 degrees, which efficiently directed the NIR light wavelength of 940 nm into the silicon.DTI serves a dual purpose in our sensor design: it acts as a reflective barrier for diffracted light and isolates the pixels to reduce crosstalk. By using highly reflective materials in the trench, the diffracted NIR light is confined within the silicon, further extending the interaction time and improving absorption. In simulations, our plasmonic diffraction structure achieved a diffraction efficiency of 49.7%, meaning nearly half of the incident NIR light was effectively diffracted into the silicon. More importantly, when integrated with the reflective DTI, the overall NIR light absorption was increased by a factor of 8.2 compared to a conventional bare silicon sensor. Specifically, the silicon absorption was enhanced to 53.5%, even with a silicon layer as thin as 3 μm, demonstrating significant improvements over traditional methods requiring thicker silicon layers. This improvement in NIR sensitivity makes the sensor highly efficient for applications requiring NIR detection, such as night vision, medical imaging, and environmental sensing. The plasmonic diffraction structure allows the sensor to capture NIR signals with greater precision and sensitivity while maintaining the compactness and cost-effectiveness of CMOS-compatible designs.

4. Plasmonic polarization color filter

We further demonstrated the potential of the plasmonic polarization color filter, fabricated from 1D periodic corrugated aluminum thin films, for wavelength and polarization selectivity. When TM-polarized light was irradiated to the corrugated metal thin film, surface plasmon resonance was excited, and which induced resonance decoupling. The light selected by the corrugation period transmits through the metal thin film by this SPR coupling and the induced decoupling, allowing for precise wavelength control. Meanwhile, TE-polarized light, which does not excite surface plasmon resonance, was reflected. The fabricated aluminum thin film filter was highly compatible with standard CMOS processes and showed durability under high temperatures and long-term sunlight exposure, making it suitable for practical applications. In spectral measurements, the filter displayed a single transmission band with a peak transmittance of 40%, demonstrating the efficiency of resonance coupling and decoupling. This filter achieved an extinction ratio of 10 dB, confirming its polarization selectivity. In summary, this plasmonic filter, both for color and polarization selectivity, offers a significant advantage in terms of enhanced sensitivity and compact system design compared to conventional systems. They hold promise for a wide range of applications, including advanced imaging systems, biological imaging, and environmental sensing.

5. Conclusion

For color filtering, we developed a plasmonic filter using periodic metal nano-gratings with concentric corrugations, enabling simultaneous visible and NIR imaging. Additionally, the introduction of a plasmonic polarization color filter based on 1D corrugated aluminum thin films demonstrated wavelength and polarization selectivity, achieving a 10 dB extinction ratio and high transmittance for TM-polarized light. This filter is highly compatible with CMOS processes and provides robust performance under high temperatures and long-term sunlight exposure.

To enhance NIR sensitivity, we employed plasmonic diffraction with deep trench isolation (DTI), which improves NIR light absorption through repeated reflections within the silicon. Simulations showed an 8.2-fold improvement in NIR absorption, with 53.5% efficiency in a 3 μm silicon layer. These advancements offer an efficient, compact, and scalable solution for multispectral imaging systems, with applications in fields such as security, biomedical imaging, and autonomous driving.

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