博士論文（要約）

Plasmonic nanofin cavity structures for spectroscopic applications

（プラズモニックナノフィンキャビティ構造を用いた分光応用）

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Metallic nanostructures with their ability to sustain surface plasmons realizing strong coupling of incident light to the structure surface have received great attention for light manipulation and various optical properties. The interaction of light with these plasmonic structures makes it possible to support subwavelength modes having strong electric field enhancement at local hot spots. These modes are determined by the structure parameters that can be designed to suit the requirements of applications. However, a main limitation of the plasmonic structures lies in far-field measurements restricted by the small area of the light coupling. The observed resonances in transmission and reflection are broad, thus hampering accurate determination of the resonance wavelength for practical utilization. Furthermore, although the relation between the size or the shape of nanostructures and the resonance wavelengths has been clarified, it is still difficult to accurately and systematically control the resonance wavelengths by simply varying of the structure parameters over a wide range, especially near infrared and infrared regime, which is of major interest for light communication, spectroscopic, biological and medical applications.

Among the reported plasmonic structures, cavity structures are promising because cavities not only support plasmonic hot spots but also provide a means to improve the resonance in a wide range of wavelengths due to cavity modes. In-plane and out-of-plane structures as two main categories of cavity structures have been reported and utilized in various optical devices. Most of the in-plane cavity-coupled structures are filled with dielectric materials, so that the surfaces with the strong field enhancement are ineffective, which is a demerit for utilization, especially sensing applications. For the out-of-plane structures, main limitations are the weak resonances due to the single direction of plasmon resonances and complicated fabrication process. To overcome the mentioned difficulties and to achieve superiority in the applications, the coupling of surface plasmons on the hot spots to hollow cavities in both horizontal and vertical directions seems to be a promising design.

In this dissertation, a gold coated nanofin-cavity structure was first designed and fabricated as a 3-dimentional suspended structure for optical filtering application in the infrared regime. Due to coupled mode of the plasmonic hot spots and the nanofin cavities, standing-wave resonances are observed in x-(horizontal) and z-(vertical) directions and an optical vortex pattern is thus generated in the cavity resulting in rotation of light direction. Therefore, a strong reflectance peak with a large reflectance modulation is obtained in the spectrum. When the nanofin cavities are further coupled to the propagating surface plasmon resonance, a strong peak with a narrow bandwidth is realized due to the stringent excitation condition. A measured reflectance peak with the narrow bandwidth defined as a full width at half-maximum reaches 92 nm with quality factor of 59.8 in the infrared regime. To utilize nanofin-cavity structure for filtering applications, the resonance wavelengths are controlled by the period of nanofin cavities and systematically tunable in a wide range of the infrared regime. Furthermore, a high angle-dependent property of the resonances is obtained by the coupled mode further utilized in optical switching. A high reflected condition of 55% reflectance can be switched to a low reflected condition of 9% reflectance by tilting the nanofin-cavity structure with a slight angle of 2° . It is noted that resonance of shorter wavelength in the near-infrared region are realized as high-order modes with a large cavity scale. The high-order modes of the nanofin-cavity structure provide a possibility to decrease the difficulty in nanostructure fabrication for short resonance wavelengths.

Besides the nanofin-cavity modes with high reflectance, the other nanofin-cavity modes with a light trapping effect are obtained at different resonance wavelengths. Main difference between the reflective mode and light trapping mode is the direction of the optical vortices. With particular optical properties, these two nanofin-cavity modes are utilized for different applications. By noting the highly symmetric electric field distributions and optical vortex patterns of the light trapping nanofin-cavity mode, a hollow U-cavity structure is designed with a mirror similar to folding the nanofin cavities. In contrast to the nanofin cavities achieving partial light trapping with symmetrical optical vortices, the U-cavity with mirrored surface plasmons supports an intense optical vortex resulting in full light trapping. Mirror symmetry results in strong light recirculation as observed in the form of further intense optical vortices. The U-cavity structure is shown to realize significant sensing performance with the intense optical vortices on the large and effective surfaces of the hollow cavities. Thanks to the full light trapping in the U-cavity structure, strong reflectance dips with narrow bandwidths at resonance wavelengths are experimentally measured with a full width at half-maximum of 14 nm and the largest high reflectance modulation quantified as the ratio between the full height and full width at half-maximum as large as 0.011 nm-1. Thanks to the intense light flow on the surface and the extended sensing surface, the

U-cavity structure achieves a high sensing performance to the changing of surrounding refractive index defined as figure of merits of 57 in the near infrared regime. The ability of the fabricated structure to work as a biosensor in a protein-ligand scheme was confirmed by the detection of avidin-biotin complex binding.

Thanks to the light trapping with the optical vortices in the U-cavities, finite arrays of U-cavities enabling integration of sensors at the microscale can be designed for micro-system and lab-on-a-chips. Under the conditions of full light trapping without propagation between the cavities, miniaturized detectors based on five cavities (about five micrometers in total length) are made possible without degradation of the sensing performance. On the basis of the light trapping behavior in finite U-cavities, an independent cavity structure was designed for practical utilization with a simpler fabrication process. A plasmonic sensor based on independent cavity structure achieves a highest figure of merit above 20 in the near infrared regime by trapping light in the cavities without light propagation or leakage due to plasmonic cavity modes.

Based on the design and fabrication techniques of the U-cavity structure, a hybrid structure consisting of metallic U-cavities separated by dielectric channels was proposed for a strong light absorption and confinement. The coupling of channel modes and horizontal surface plasmon modes with a stringent restriction supports light concentration by antinodes at the channel entrances and strong light confinement by nodes at the channel exits. Therefore, the hybrid structure sustains strong and narrow-band absorptance resonances. The fabricated hybrid structure achieves a strong and narrow-band reflectance dip representing strong absorption with full width at half-maximum as small as 9 nm and the lowest reflectance of 6.6% is obtained with modulation larger than 63%. The resonance dips can be designed in a wide range of wavelengths with narrow bandwidths by coupled to different channel modes. It is noted that the tunability of the single band is realized by varying the U-cavity width instead of varying the channel width, thus dissociating the control of the resonance wavelength from the structure used to confine light. Due to the high angle-dependency of the horizontal surface plasmon mode, split resonances by varying light incident angle are demonstrated in the experiments. Similar to the optical switching property of the nanofin-cavity structure, reflectance variation lager than 40% is obtained within 1°. Comparing with light trapping with the optical vortices in the large and hollow U-cavities, the light is confined in the narrow channels of the hybrid structure. Thus effective absorption is realized with the extremely narrow bandwidth and the large modulation.

In summary, the out-of-plane plasmonic cavity structures based on the 3-dimentional nanofins are demonstrated by the well-designed nanofabrication process. Thanks to the superior properties of these structures, light is manipulated with high reflectance, transmittance, and absorptance at specific resonance wavelength in a wide range of visible to infrared regime in the experiments. Fundamental principles of all structures are valid from ultraviolet to terahertz regime. The plasmonic structures based on the nanofins offer new possibilities for applications in filtering, switching, biosensing, optoelectronic detection and plasmonic lasing.