Plasmonic Nano Resonators Using Asymmetric-Double-Bar Metamaterials

著者	Moritake　Yuto
学位授与機関	Tohoku University
学位授与番号	11301甲第16963号
URL	http://hdl.handle.net/10097/64377

もり　たけ　ゆう　と
氏　　　　　　　名　森　竹　勇　斗
研究科，専攻の名称　東北大学大学院工学研究科（博士課程）ナノメカニクス専攻
学 位 論 文 題 目　Plasmonic Nano Resonators Using Asymmetric-Double-Bar Metamaterials
論 文 審 査 委 員　主査　東北大学教授　羽根　一博　東北大学教授　小野　崇人
東北大学教授　石原　照也　東北大学准教授　金森　義明

論文内容要約

Recently, metamaterial resonators; arrays of plasmonic nano resonators, are paid significant attentions by researchers due to their potential to realize applications with exciting functionalities, such as spectral control, refractive index sensing, beam steering, light emission control, perfect absorption, polarization conversion, and so on. In metamaterial resonators, metamaterial resonators with Fano resonance have attractive features including steep spectral responses, high quality factors (Q-factors), and large phase shifts. By using Fano resonance in metamaterial resonators, sensors, filters, light emitting devices, light absorbers, and phase shifters can be realized. Although various metamaterial resonators exhibiting Fano resonance have been reported, especially, demonstration of metamaterial resonators with Fano resonance in the optical region is important to realize realistic applications. Moreover, since performance of applications using metamaterial resonators with Fano resonance strongly depends on characteristics of metamaterial resonators, improvement and expansion of functionalities of Fano type metamaterial resonators are needed.

Recently, asymmetric-double-bar (ADB) metamaterials have been proposed as metamaterial resonators with Fano resonance. ADBs are composed of only two bars with slightly different bar lengths and can be the simplest structures in metamaterial resonators with Fano resonance. Since optical metamaterials need to ultrafine structures in the order of several tens of nanometers, ADBs have advantage for fabrication due to its simple structure. Although ADB metamaterials are promising structures for realizing Fano resonance in the optical region, ADB metamaterials have not been experimentally demonstrated in the optical region. By applying ADB metamaterials into device using metamaterial resonators with Fano resonance, various functionalities of metamaterial devices such as fluorescence control, multiple resonances, improved Q-factors, and dynamic spectral control, can be realized in the optical region.

In the dissertation, to show the potential of ADB metamaterials for realizing metamaterial devices operating in the optical region, design, fabrication, and demonstrations of metamaterial resonators using ADB metamaterials were described. Moreover, in demonstrations, problems in metamaterial resonators

operating in the optical region were solved using ADB metamaterials.

In chapter 2, to demonstrate Fano resonance of ADB metamaterials in the optical region, ADB metamaterials were designed and fabricated. The mode hybridization in ADB structures was analyzed by a coupled classical oscillator model. Dependence of gap and thickness of the bars on resonant wavelength of Fano resonance was investigated. Fano resonance was insensitive to the gap in the case of the designed structures and thicker metal bars were preferable for higher Q-factors. ADB metamaterials were fabricated by micromachining and a lift-off method and fine length control of the bars in the order of several nanometers was achieved. Measured spectra clearly showed sharp Fano resonance around λ = 1200 nm due to weak asymmetry of the ADB structures. Resonant wavelengths and Q-factors were estimated from difference absorption spectra and dependence of asymmetry was investigated. Resonant wavelengths of Fano resonance shifted to shorter wavelength side with increase in asymmetry. Q-factors were reduced with increase in asymmetry due to radiative loss and the highest quality factor of Fano resonance was 19.9. Simulated values of resonant wavelengths and Q-factors showed good agreement as the experimental results. Consequently, Fano resonance in ADB metamaterials in the optical region was successfully verified in experiments for the first time.

In chapter 3, wavelength tuning of Fano resonance of ADB metamaterials was demonstrated and effects of metal loss in the optical region were evaluated. Wavelength tuning and evaluation of effects of metal loss is mandatory factor to apply ADB metamaterials into actual applications. ADB metamaterials with different sizes were fabricated by a lift-off method and optical spectra were measured. For the fabricated ADB metamaterials with different sizes, experimental spectra clearly showed Fano resonance at around wavelengths of 1500, 1200, and 750 nm. Characteristics of Fano resonance were estimated from optical spectra and dependence of asymmetry was studied. Resonant wavelengths linearly shifted with size change of the structures although a scaling law doesn't hold rigidly in the optical region due to small conductivity and dispersion of metal. Because the effective wavelength of plasmons is a linear function of the size of the structures due to Drude type dispersion of metal, resonant wavelengths show linear relation with a size of unit cell structures. Q-factor and sharpness of the Fano resonance increased with decrease in asymmetry because of a small radiative loss in small asymmetry conditions. In the visible region, qualities of resonance were relatively small compared with those in the near-infrared region. Consequently, a design method for wavelength tuning of Fano resonance in ADB metamaterials was established and it is was revealed that qualities of resonance are relatively low in the visible region.

In chapter 4, manipulation of quantum dots (QD) fluorescence was proposed and demonstrated using

ADB metamaterials. Using wavelength tuning based on a scaling law, coupling between Fano resonance and QDs were achieved. Dependence of the shape of sub-wavelength unit cell structures on fluorescence manipulation was also investigated. ADB metamaterials hybridized with QDs dispersing in a polymer were fabricated and optical spectra show Fano resonance at wavelengths of around 1350 nm corresponding to an emission wavelength of QDs. To measure fluorescence of QDs on metamaterials formed in a 100 μm×100 μm area, a microscopic fluorescence measurement system was constructed. From fluorescence measurements, strongly polarized fourfold enhancement was observed, resulted from Purcell effect due to coupling between QDs and Fano resonance in ADB metamaterials. Shifts of emission peaks and change in Q-factors of modified fluorescence depending on unit cell structures were confirmed experimentally. And these characteristics variations were well reproduced by analysis using absorption peaks of Fano resonance. Consequently, fluorescence control by changing unit cell structures of ADB metamaterials was successfully demonstrated.

In chapter 5, multiple Fano resonances in optical metamaterials were proposed and experimentally demonstrated by combination of two different sized ADB structures. Combination of two different sized ADBs created a new mode named as an extended antiphase mode, in which oscillations of dipoles at the bars are in-phase in one ADB structures, while anti-phase among different sized ADBs. By changing the size of ADBs, resonant wavelengths were controlled and various spectral shapes were obtained. Consequently, multiple Fano resonances in optical metamaterials were successfully demonstrated using ADB metamaterials.

In chapter 6, enhanced Q-factors of Fano resonance in ADB metamaterials using manipulation of unit cell configurations in the optical region were proposed and demonstrated. An alternately flipped configuration of unit cells was introduced in ADB metamaterials. Q-factors of Fano resonance at wavelengths around 1500 nm were extracted from absorption spectra and dependence of asymmetry was studied. The Q-factors for the alternately flipped configuration were higher than those for a non-flipped configuration at respective asymmetry. The enhancement of the Q-factors was qualitatively expressed by dipole-dipole interactions in ADB metamaterials. Destructive interactions led reduction of a net dipole moment in the alternately flipped configuration which resulted in a small radiative loss. Consequently, improvement of Q-factors of Fano resonance successfully demonstrated using ADB metamaterials by manipulating unit cell interactions.

In chapter 7, I proposed, fabricated, and demonstrated the electrically reconfigurable metamaterials operating in the optical region using ADB metamaterials. By using MEMS technologies, Fano resonance in

ADB metamaterials was dynamically controlled. Dynamical spectral control was a result from change in mutual interactions among unit cells. Mechanical motion was realized by using electrostatic force between beam structures and a ground plate. Complementally ADB metamaterial structures engraved on beam structures are used to realize Fano resonance, which is manifested by Babinet's principle. The device is actuated electrically and arbitrary metamaterial designs are applicable. Consequently, dynamic control of Fano resonance using electrically reconfigurable metamaterial resonators in the optical region was successfully demonstrated using MEMS actuated ADB metamaterials for the first time.