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論　文　内　容　の　要　旨

氏　名　（　大橋　慶郎　）	
論文題名	**Plasmonic Nanolens composed of Metallic Nanorod Chains for Color Nanoimaging with High Spatial Resolution** （高空間分解能カラーナノイメージングのための金属ナノロッド鎖プラズモニックナノレンズ）

論文内容の要旨

Plasmonics-based nanoimaging techniques have recently attracted much attention because of the use of confined light at the nanoscale for super-resolution imaging in these techniques. For one of the practical uses, applying the confined light excited at the apex of a metallized nanosize tip, super-resolution imaging with the visible light has been demonstrated, which was impossible with ordinary far-field optical apparatuses and techniques due to the diffraction limit. As another type of the nanoimaging technique, a recent report theoretically proposed that plasmonic nanolens composed of well-designed metallic nanostructures, can be a novel and promising optical imaging technique to achieve high spatial resolution in nanoimaging.

Plasmonic nanolens consists of multiple metallic nanorod chains arranged in a 3-dimension (3D) tapered shape. In the nanolens, each nanorod chain plays an important role for color nanoimaging of nanosize samples via plasmonic interaction between the adjacent nanorods in the chain and the tapered structure of the chains. And there are two important features of the plasmonic nanolens for image formation, where the one is to transfer near-field light originating from the sample along the chains, and the other is to magnify near-field image of the sample with the tapered arrangement of the chains. Contribution of these features in the plasmonic nanolens enables to realize color nanoimaging with high spatial resolution in the visible range of light. Although the plasmonic nanolens has a great potential as a new super-resolution imaging device, the experimental demonstration of a nanolens has still been challenging in the fabrication due to the complicated 3D tapered structure even with advanced nanolithographic techniques. In order to show the experimental feasibility of a plasmonic nanolens, I experimentally studied the important features of near-field transfer and image magnification with simplified metallic nanostructures. The concept demonstration of these features is an important step forward to realize a 3D plasmonic nanolens. In this dissertation, therefore, I discussed the experimental demonstration of the concept on the plasmonic nanolens as well as I mentioned how well-designed metallic nanostructures suitably work in plasmonics-based nanoimaging techniques.

In this study, I have constructed my dissertation with 6 chapters. After introducing my study in Chapter 1, I started from explaining the basics of plasmon properties in metallic nanostructures and its applications in Chapter 2. In Chapter 3, I introduced an application of plasmonics as nanoimaging techniques. In the classical optical microscopy working in the far-field, there is fundamental limitation to achieve high spatial resolution. I explained the resolution limit in the classical optical microscopy, and how plasmonics-based nanoimaging techniques overcome the limitation. In addition, I explained the controllability of plasmon resonance with metallic nanostructure size for nanoimaging. As one of the examples, I introduced the method to tune the size of metallic nanostructures through thermal deposition and annealing. In Chapter 4, I introduced plasmonic nanolens composed of a tapered arrangement of multiple metallic nanorod chains as a new type of nanoimaging technique, as well as showing previous research on some types of plasmonic nanolens. For image formation with the plasmonic nanolens, each nanorod chain plays important roles to produce near-field transfer via plasmonic coupling between the neighboring nanorods in the chains and image magnification by a tapered shape. Therefore, in Chapter 5 and 6, I explained experimental demonstration of these important features of near-field transfer and image magnification with metallic nanorod chains. To realize plasmonic nanolens composed of a 3D tapered arrangement of metallic nanorod chains, prospective fabrication method was also discussed. Finally, I ended up the thesis by giving conclusions of my work.

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論文審査の結果の要旨及び担当者

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論文審査担当者		(職)	氏　名
	主査	教授	バルマ　プラブハット
	副査	教授	井上　康志
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論文審査の結果の要旨

This dissertation discusses about a plasmonic nanolens, which is capable of making color images of nano-sized subwavelength objects by magnifying and spatially resolving the objects. Although there are a few techniques for super-resolution imaging, plasmonics-based nanoimaging techniques are much attentive because they use confined light at the nanoscale to achieve super-resolution in optical imaging. While most of these techniques rely on scanning the confined light for imaging a sample, plasmonic nanolens provides a new concept for direct imaging of a sample without scanning. The concept of a plasmonic nanolens was discussed a few years ago, however, it was never demonstrated in experiments. The reason behind this is that a nanolens is made of a complicated 3D arrangement of metallic nanorods, and fabrication of such a complicated arrangement is extremely challenging. This dissertation takes the first step of this challenge, and experimentally proves the concept of a nanolens for 1D and 2D arrangements of nanorods. Main points of the research in this dissertation are summarized below.

- A plasmonic nanolens is made of metallic nanorod chains that are arranged in a conical design with a certain taper angle. Near-field light emitted from a sample placed near one end of the nanorod chains can couple with the plasmons of the first nanorod in the chain, which consequently couples to the next nanorod and finally an image is obtained at the other end of the nanorod chain. Due to the taper angle, the distance between the nanorod chains increases as the signal moves further, and hence a magnified image is obtained at the other end. This dissertation attempts to prove the concept of image transfer through a single nanorod chain (1D) by synthesizing gold nanorods and then arranging them inside a FIB-fabricated trench to obtain a nanorod chain with desired gaps between the nanorods. By placing some quantum dots (QD) at one end of the chain, illuminating them by laser light, and then detecting the fluorescence signal at the other end of the chain, the first part of the concept of nanolens is experimentally proved.
- In the next step, a 2D structure is fabricated by synthesizing silver long nanowires, placing them in X-shape and then milling out some gaps using FIB to obtain nanorod chains at certain taper angle. By placing two QD sources separated by subwavelength distance near one end of the nanorod chains and then observing spatially resolved fluorescence signals at the other end of the chains, the concepts of super-resolution and image magnification were experimentally proved.
- In order to experimentally demonstrate the concept of a plasmonic nanolens, this dissertation also shows numerical simulations to optimize all the parameters used in fabrication.
- At last, with the experimental demonstration of the concept of plasmonic nanolens, a unique and brand-new super-resolution technique was suggested, which is capable of not only super-resolution, but also color imaging and magnification.

Thus, this dissertation has shown great potentials to benefit diverse research fields that need super-resolution in optical imaging by experimentally proving the concept of magnified color nanoimaging in plasmonic nanolens. Overall, the referees found consistent consideration and strategies to demonstrate the concept of plasmonic nanolens. Therefore, the referees have accepted that this dissertation has remarkable achievements and it certainly deserves a doctoral degree.