別紙４（課程博士）

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Abstract

論文内容の要旨　(博士)

Title of Thesis 博士学位論文名	MEMS 技術を用いた表面プラズモンの異常透過制御技術の研究 (A study on control technique of surface-plasmon extraordinary transmission using MEMS technology)

(Approx. 800 words)

(要旨　1,200 字程度)

表面プラズモン異常透過現象とは，金属微細周期構造（ナノグレーティング又はナノホール）に光が入射した際，構造に依存する表面プラズモンの励起波長のみが金属微細周期構造を透過する現象である．この現象は波長選択性や電場増強効果を持ち，撮像素子，表示素子，およびバイオ医療用センサなどに広く応用研究が行われている．しかし，光透過特性は周期構造の設計段階で決定されてしまい可変することができず，受動素子としての機能しか得ることができない課題があった．本論文では，金属微細構造の周期構造を制御可能な静電Micro-electro-mechanical system（MEMS）アクチュエータを一体化することで，表面プラズモン異常透過の励起波長の連続可変制御技術を確立することを目的とする．

微細周期構造を制御する方法として平行平板型と櫛歯型の静電MEMSアクチュエータを新規に提案した．平行平板アクチュエータを並べた構造をサブ波長格子と見立て，駆動電圧3.4 Vにより可視域の透過スペクトルの制御に成功した．さらに，平行平板型は可動部の質量が小さいため1 μs以下の応答速度を持つことが期待できる．しかし，サスペンション部を設けた平行平板型ではバネ定数が小さく，可動格子の横変位は得られない．したがって，平行平板型による周期構造制御は，通信や表示装置に向けた低消費電力光スイッチング技術としての応用が期待できる．

表面プラズモン異常透過現象の励起波長制御には，周期構造製作後に構造変化を与える必要がある．しかし，既に報告された素子の多くは周期構造が基板に固定されており，構造を任意に変更することは難しい．よって，微細周期構造として中空のAlナノワイヤアレイより構成される中空波長選択フィルタを提案する．リフトオフとプラズマフリーのXeF_2エッチングの併用により，中空Alナノワイヤアレイを周期構造を保持した状態での形成に成功した．周期450 nmから600 nmを持つ中空Alナノワイヤアレイにおいて，ワイヤ周期150 nmの拡張で励起波長が159 nm長波長側へシフトすることを確認した．また，Alナノワイヤアレイの偏光依存性を確認し，無偏光の光により表面プラズモン励起波長の観測が可能であることを示した。これらの結果より，MEMSアクチュエータによる周期拡張により励起波長制御の可能性を示した．

表面プラズモン励起波長の連続可変制御技術として，Alサブ波長格子と静電櫛歯アクチュエータを一体化した表面プラズモン可変フィルタを提案する．周期500 nmを持つAlサブ波長格子を静電櫛歯アクチュエータにより均一に周期拡張する．表面プラズモン可変フィルタに駆動電圧60 Vを印加し，可動電極の710 nmの横変位が得られ，励起波長は542 nmから668 nmまで連続的にシフトした．この際，周期は142 nm拡張したと考えられる．これらの値は理論値と一致しており，MEMSアクチュエータにより表面プラズモンの異常透過光を制御することに成功したと言える．励起波長

の連続可変制御の実現により，表面プラズモンの異常透過現象を能動素子として応用することが可能となり，単一素子で複数の波長を選択的に透過する可変プラズモニックカラーフィルタ等の実現が期待される．

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The excitation of surface plasmons (SPs) leads to an electric-field enhancement at the interface of the metallic periodic structures and dielectric materials and spatially provides functional selectivity of optical wavelengths. This optical phenomenon is called extraordinary optical transmission whose conditions depend on the periodic structure. The extraordinary optical transmission generated by excitation wavelengths is applicable to chemical and biomedical sensors by changing the surrounding dielectric constants. Additionally, the spatial transmission light is currently being intensively investigated for application to new color filters. On the other hand, the spatial control of the excitation wavelengths after the fabrication of the metallic periodic structure has been examined. This function enables the switching and variability of the transmitted light and electric-field intensities and allows for the miniaturization of optical devices. Additionally, spatial control eases the readjustment of the transmission spectrum. However, these are difficult after the fabrication of the metallic periodic structure because metallic subwavelength structures are fixed on bulk substrates. In this study, the control technique of the surface-plasmon-based extraordinary transmission using micro-electro-mechanical system (MEMS) technologies is realized.

An electrostatic parallel-plate actuator and a comb-drive actuator were newly proposed for changing the metallic period. Movable subwavelength gratings employing electrostatic parallel-plate actuators were successfully demonstrated to control transmission spectra in the visible region by applying a drive voltage of 3.4 V, which were expected to have a fast response in the order of submicron seconds. However, the tuning range was not sufficient to cover all of the visible regions, because the parallel-plate actuator exhibits a nonlinear pull-in behavior. A movable electrode is brought into contact with a counter electrode when the gap between the electrodes is smaller than about one-ninth of the initial gap. Therefore, parallel-plate actuators can provide the fast switching function for SP-based devices.

Freestanding aluminum (Al) nanowire arrays patterned through non-plasma dry etching and the lift-off technique were proposed for controlling excitation wavelengths after the fabrication of the metallic periodic structure, and the proposed fabrication process was demonstrated to keep the freestanding periodic structure. An array of Al nanowires was deployed over a through hole formed by sacrificial silicon etching. The period of the Al nanowire arrays is the dominant

structural parameter in determining the excitation wavelength of SPs for a given material configuration. The Al nanowire arrays were designed with the same Al wire width under the assumption of operation using the MEMS actuator. The SP-based excitation wavelength was red-shifted 159 nm by increasing the period of the Al nanowire arrays from 450 nm to 600 nm. The 400-nm-pitch freestanding Al nanowire array excited the wavelength in an ultra violet. The polarization dependency of the freestanding Al nanowire array was observed, and the excitation wavelength of SPs was observed by the incident light of non-polarized light and TM plane wave. In addition, a miniaturization of the freestanding Al nanowire array was investigated for the low power operation by a MEMS comb-drive actuator, and obtained the excitation wavelength from the pixel size of 5 μm square including 10 Al nanowires. Therefore, a possibility to realize a freestanding plasmonic color filter was shown, which is possible to apply to continuous control of the SP-based excited wavelength by integration with the MEMS actuator.

A new method for continuously controlling SP-based excitation wavelengths using a nanomechanically stretched metal subwavelength grating was newly proposed. The Al subwavelength grating with period of 500 nm was integrated with electrostatic comb-drive actuators to expand the metal subwavelength period, which allowed continuous control of the dependent excitation wavelength. The excitation wavelength then shifted from 542 to 668 nm by increasing the applied voltage from 0 to 60 V. In this case, movable electrodes were laterally shifted by approximately 710 nm, and a grating period of 640 nm was expected. The excitation wavelength was shifted in accordance with the square of the applied voltage, which was clearly influenced by the variations in the period of the Al subwavelength grating. Therefore, continuous control of SP-based excitation wavelengths was successfully demonstrated, and this new tuning method can provide the functions of readjustment and continuous tuning for SP-based devices. Proposed techniques can be applied to active elements such as a tunable color filter. By applying proposed techniques, the realization of the tunable plasmonic color filter that is possible to selectively transmit multicolor is expected. In addition, the proposed tuning method for SPs can use other materials such as gold and silver instead of Al. By using other materials, the tuning range of the excitation wavelength can be changed from the visible to near-infrared region. Thus, the proposed continuously controlling technology will have wide application for optical active elements at various wavelength bands.