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研究課題名（和文）On-chip modulation of optical signals using plasmonic induced phase transitions for realizing all-optical circuitry

研究課題名（英文）On-chip modulation of optical signals using plasmonic induced phase transitions for realizing all-optical circuitry

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研究成果の概要（和文）：本研究の目的は実装面積とエネルギー消費を抑えた集積化オンチップデバイスで光学信号を光で制御することである。このような光学的手法による光学信号の高速変調を実現するために、強相関金属酸化物相転移材料の時間ダイナミクスについて分析を行った。これにより、制御光がテラヘルツ帯の周波数において効率良く信号光を調整することができ、制御光の光度に対し線型に信号光を調整できることを示した。また、このとき微小ではあるが、望ましくない遅れて変調された成分も存在している。ここで調べられた材料を用いた微細な光制御の光学変調器の設計を提案し、消光比の最適化を行った。

研究成果の学術的意義や社会的意義
The large all-optical modulation reported enables to modulate light using light and achieve all-optical information processing. All-optical information processing is superior to conventional electronic devices because light can have superior modulation speeds and can propagate without loss.

研究成果の概要（英文）：Our research goal is to modulate light (signal) using light (control) in an integrated on-chip device with reduced footprint and energy consumption. In order to achieve this high-speed modulation of an optical signal by optical means, we have investigated the time dynamics of strongly correlated metal oxide phase-transition materials and found that, under a low-intensity regime for the control light, the signal light can be modulated efficiently at a frequency in the terahertz range. Under this regime, the modulation is linear with the intensity of the control light and not related to the material phase transition. Also, an unwanted slow but small component is present in the modulation. Design of an all-optical modulator with a small footprint employing the studied materials is presented. The proposed all-optical modulator consists of a waveguide modified by a sub-wavelength plasmonic grating with phase-transition material filled nanogaps and achieves a high extinction ratio.

研究分野：Nanostructures for energy conversion and sensing

キーワード：ナノ光学　全光スイッチ　プラズモニクス　ナノ構造

１．研究開始当初の背景

All-optical information processing is superior to conventional electronic devices because light can achieve faster modulation speeds and can propagate without a loss (no ohmic loss). The realization of all-optical information processing relies on the ability to modulate light using light, that is, to develop an integrated device that switches light with light in the same way as a transistor switches an electronic signal with the help of another electronic signal. Such all-optical modulators would consume less energy and have a small footprint amenable for on-chip integration so that advanced optical communication systems (guiding and modulating optical signals in their optical form without electrical conversion) could be realized.

All-optical modulators based on strongly correlated metal oxides (e.g., VO_2) have been proposed. As these materials undergo an insulator-metal transition, their optical properties change drastically so that a large modulation of the light intensity is obtained. The insulator-metal transition can be induced optically under high light intensity. Although there is still no consensus for the description of the optically-induced insulator-metal transition, it is thought that the mechanism of the insulator-metal transition should follow the Mott-Hubbard description and exhibit a relatively slow recovery. On the other hand, the behavior of strongly correlated metal oxide materials under low light intensity (before the optically induced phase transition occurs) is not well understood and characterized.

２．研究の目的

The research goal is to modulate light (signal) using light (control) at a rate faster than terahertz in an integrated on-chip device with reduced footprint and energy consumption. For this purpose, we investigate the time dynamics of the strongly correlated metal oxides VO_2 and NbO_2 under low intensity of the control light. Also, we propose a design for a miniaturized low-power consumption all-optical modulator.

３．研究の方法

The methodology consists of three steps, namely, 1) the development of a pump-probe optical setup to analyze the fast dynamics of the studied materials, 2) the synthesis of the materials and the analysis of the fast dynamics of these materials using the pump-probe setup developed in step 1), and 3) the design of an integrated modulator.

４．研究成果

1) A pump-probe optical setup (Figure 1) was developed employing a delay line and a femtosecond laser. The optical excitation (pump) used a wavelength of 766 nm, and the change in the sample was probed at a wavelength of 1550 nm (C-band used in the telecommunication). Alignment of the sample with respect to the pump and probe beams was realized using a visible camera and a near-infrared camera (Figure 2). As seen in Figure 2, the sample can be analyzed in both the transmission and reflection modes. The setup offers a time resolution of about 200 fs. Low noise is achieved by employing lock-in amplification with a chopper and reduction of the noise can be seen in Figure 3. Moreover, the setup permits re-pump analysis (analysis of two consecutive pump pulses separated by a delay of 100 ps) to clarify the response of the material. Also, a spatial filter was developed to separate the excitation beam from the beam transmitted through a device such as a waveguide as seen in Figure 4.

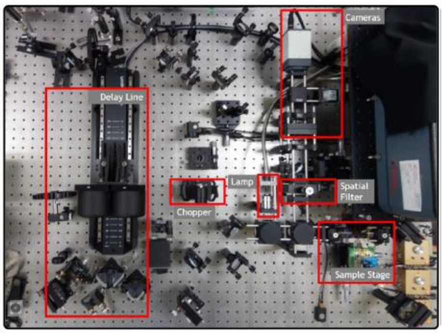

Figure 1

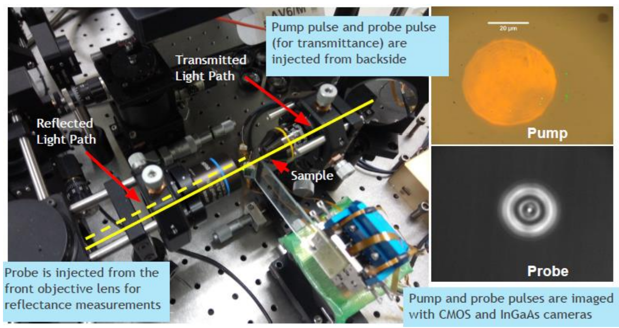

Figure 2

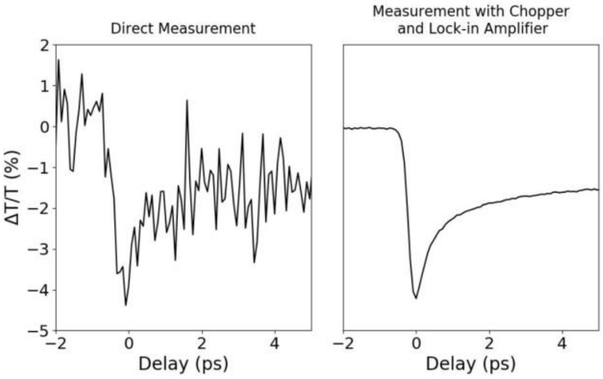

Figure 3

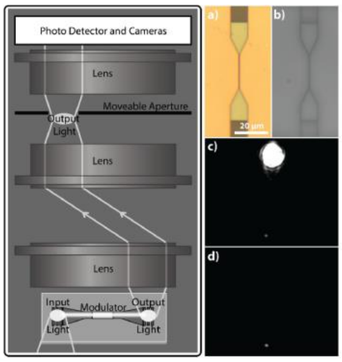

Figure 4

2) The strongly correlated oxides VO_2 and NbO_2 have been deposited in the form of thin films using a pulsed laser deposition system. The pump-probe results for a NbO_2 film are shown in the transmission and reflection modes in Figure 5. A large modulation of a few percents was found in both the transmission and reflection modes. The time response of the fast component of the observed modulations is of the order of a ps. These observed large and fast modulations should enable the practical development of all-optical modulators. Under the low-intensity regime studied here, the investigated materials are reported to exhibit a full recovery in the literature. However, we found that the response of the materials results in a fast modulation (of the order of a ps) and a slow contribution with a decay time of the order of a nanosecond. To clarify the mechanism of the low-intensity regime, the modulation as a function of the pump intensity was measured. The observed relation between the modulation and the pump intensity was found to be linear, thus confirming that the regime investigated does not involved the optically indiced phase transition (no threshold for the insulator-metal transition is observed). Furthermore, the re-pump experiment confirmed the linearity of the modulation response, that is, two delayed pump pulses of the same intensity gave the same modulation, a result that cannot be obtained for a modulation induced by a nonlinear mechanism such as a metal-insulator transition. In summary, the modulation at low intensity of the pump is a linear process not related to the metal-insulator transition and involves the combined effects on the refractive index of photo-induced free carriers as well as bandfilling. The slow contribution to the modulation would, therefore, be explained by phonon relaxation. Similar results were obtained with VO_2. Finally, the decay time of the slow component was decreased to approximately 100 ps by reducing the amount of active material. Both decreasing the film thickness and patterning the active layer to form an array of squared nanostructures were used to decrease the decay time of the slow component.

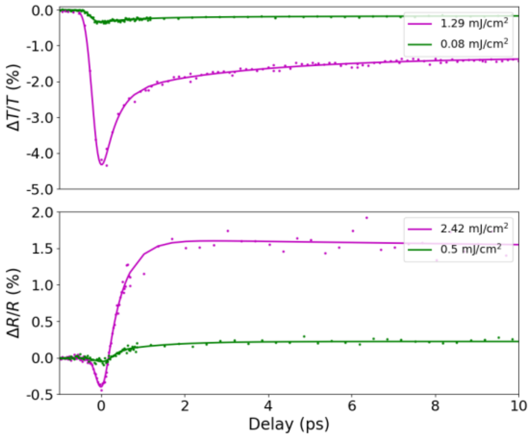

Figure 5

Additionally, the optically-induced phase transition was studied with VO_2 to confirm the differences in the time dynamics between the low-intensity regime and the high-intensity regime. Evidence for the presence of the monoclinic metal state in the high-intensity regime was found.

The above results are under consideration for publication.

We also investigated the effect of a plasmonic structure on the insulator-metal transition. Here, the all-optical modulator is realized by integrating the phase-transition material into a resonant plasmonic nanostructure. Upon triggering a phase transition by plasmonic excitation, the proposed modulator changes from being transparent to the signal light to absorbing. This change in the optical properties is made possible by pumping the modulator with a control light that excites the resonance of the plasmonic nanostructure. The resonance of the plasmonic nanostructure enhances the electric field which should help to trigger the insulator to metal transition. We designed the plasmonic nanostructure to be used in the switching of strongly correlated metal oxide materials, fabricated the plasmonic nanostructure with VO_2, and found that the designed plasmonic nanostructure can be used to decrease the threshold of the pump intensity for the insulator-metal transition.

3) A schematic of the proposed optical modulator using the highly correlated metal oxides as the active material is provided in Figure 6. The proposed optical modulator consists of a waveguide modified by a sub-wavelength plasmonic grating with phase-transition material filled nanogaps and was analyzed theoretically. The control light excites gap plasmons within the nanogaps, resulting in an enhancement of photoabsorption. The photoexcited electrons trigger a photo-induced insulator-to-metal phase transition. Upon the phase change, the waveguide cannot transmit the signal light, which is instead absorbed in the hybrid nanostructure. Figure 7 shows the light propagation through the waveguide device in the ON state (left) and in the OFF state (right). The optimized design achieved an extinction ratio of 26.8 dB/μm. The signal light and control light are both transmitted through the same waveguide, allowing a fully integrated design with on-chip data processing. Although the device has been optimized using simulation, it is still a challenge to demonstrate such a device as the materials of choice used in all-optical switching do not perform as expected.

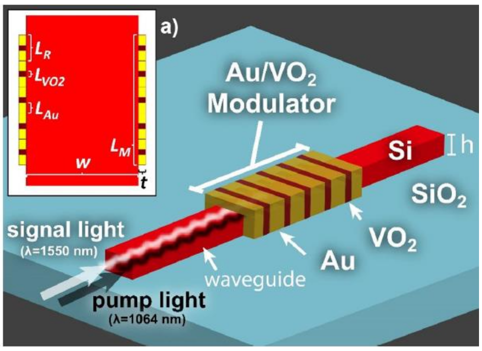

Figure 6

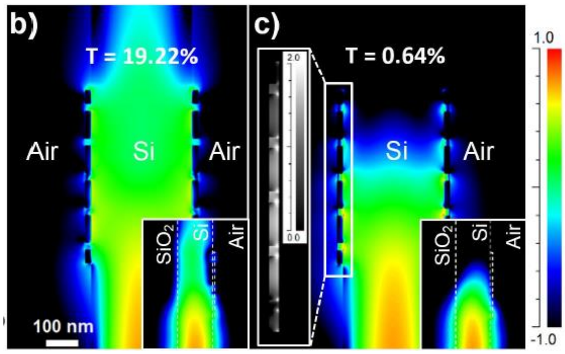

Figure 7

５．主な発表論文等

〔雑誌論文〕（計 4 件）

[1] J. K. Clark, Y.-L. Ho, H. Matsui, J.-J. Delaunay, “Optically Pumped Hybrid Plasmonic-Photonic Waveguide Modulator using the VO2 Metal-Insulator Phase Transition,” IEEE Photonics Journal, 10, 4800109, 2018.
DOI:10.1109/JPHOT.2017.2784429

[2] Y.-L. Ho, J. K. Clark, A. Syazwan A. Kamal, J.-J. Delaunay, "On-Chip Monolithically Fabricated Plasmonic-Waveguide Nanolaser," Nano Letters, 18, 7769-7776, 2018.
DOI:10.1021/acs.nanolett.8b03531

[3] Z. Wang, J. K. Clark, Y.-L. Ho, B. Vilquin, H. Daiguji, J.-J. Delaunay, “Narrowband thermal emission from Tamm plasmons of a modified distributed Bragg reflector,” Applied Physics Letters 113 (16), 161104, 2018.
DOI:10.1063/1.5048950

[4] Z. Wang, J. K. Clark, Y.-L. Ho, B. Vilquin, H. Daiguji, J.-J. Delaunay, “Narrow-band thermal emission realized through the coupling of cavity and Tamm plasmon resonances,” ACS Photonics, 5, 6, 2446-2452, 2018.
DOI:10.1021/acsphotonics.8b00236

〔学会発表〕（計 1 件）
[1] J. Kenji Clark, Ya-Lun Ho, Hiroaki Matsui, Jean-Jacques Delaunay, "Optically pumped hybrid plasmonic-photonic waveguide modulator using the VO2 metal-insulator phase transition," The 9th International Conference on Surface Plasmon Photonics (SPP9), May 26-31, 2019, Copenhagen, Denmark.

〔図書〕（計 0 件）

〔産業財産権〕
○出願状況（計 0 件）

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ホームページ等

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