Electrically-driven Permeability-controlled Optical Modulator using Mach-Zehnder Interferometer with Metamaterial

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Abstract: An electrically-driven permeability-controlled GaInAsP/InP optical modulator was experimentally demonstrated using Tri-gate metamaterial structure. An extinction ratio of 6.9 dB was obtained at 1550-nm wavelength with a gate swing of 2-12 V.
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1. Introduction

Optical metamaterials offer new opportunities for innovation in the field of electromagnetic parameter design, such as the design of permittivity ε and permeability μ [1, 2]. The major focus of attention is to create artificial materials with unique ε-μ values that cannot be observed in any existing media and to take advantage of these expanded parameters for better control of electromagnetic waves. One of the next trends is to think of metamaterials as devices, where the structuring of metal and the hybridization with functional agents brings new functionality [3]. Especially, introducing optical metamaterials into actual photonic devices poses an exciting challenge. Much effort has been expended in the development of advanced optical applications using the concept of metamaterials; leading examples of such applications include a fiber-based metamaterial device that can be used as a nanoscale light source [4] and a Si-based metamaterial modulator that can perform negative-index tuning [5].

In this paper, we demonstrate InP-based optical devices combined with metamaterials to show the possibility of permeability control on the semiconductor-based photonics platform. As an actual example, we report an electrically-driven permeability-controlled optical modulator, which shows great promise for using both the permittivity and permeability in semiconductor-based actual photonic devices.

2. Device structure and characteristics of Tri-gate controlled metamaterial

The permeability-controlled optical modulator is shown in Fig. 1(a). It consists of a Mach-Zehnder interferometer (MZI) made with a GaInAs/InP/GaInAsP multi-epitaxial layer on an InP substrate, with 'Tri-gate controlled metamaterial (TGM)' attached on the MZI arms. The TGM consists of an array of Ti/Au split-ring resonators (SRRs) (Fig. 1(b) lower). The surface of the arms is fin-shaped, and each SRR ring wraps the fins on three sides to form the tri-gate structure. A controlling gate is placed on the TGM to couple capacitively to the SRRs. The TGM provides dynamic tuning of permeability with accumulated carriers in the fins under a gate bias. Figure 1(b) upper shows electron densities in the fin at V_g = 10 V, calculated by 3-dimensional TCAD simulation. By introducing a tri-gate structure, majority charge carriers are efficiently induced in the fin. In this situation, we can change a gap capacitance with an increase of a carrier concentration, thereby changing the effective permeability of the TGM.

Before fabricating actual devices, we first prepared a TGM array on InGaAs/InP wafer to obtain the fundamental information for resonance frequency. After fin formation (75-nm width, 60-nm height), a metal ring array (consisting of 10-nm thick Ti and 30-nm thick Au) was fabricated using electron-beam lithography (EBL) followed by 10-nm Al_2O_3 atomic layer deposition (Fig.

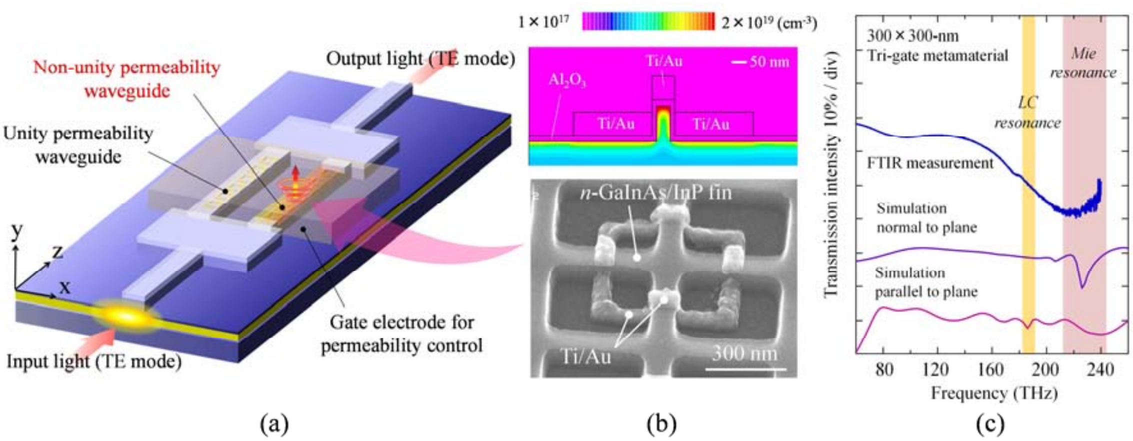

Fig. 1 (a) Permeability-controlled optical modulator consisting of InGaAsP/InP Mach-Zehnder interferometer with Tri-gate metamaterials. (b) SEM image of TGM unit cell (lower). Electron densities in the fin at V_g = 10 V, calculated by 3-dimensional TCAD simulation (upper). (c) Normal-incidence transmittance spectra for 300 × 300 nm TGM.

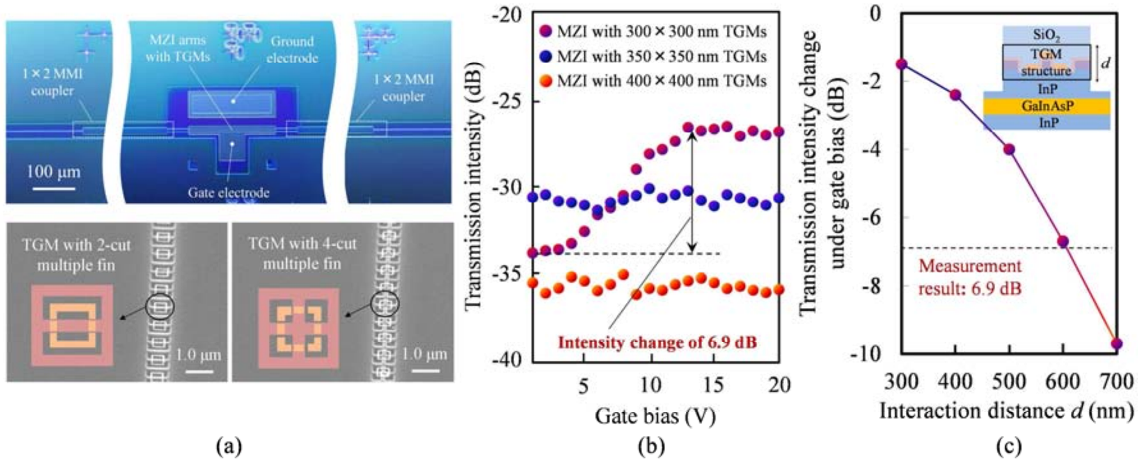

Fig. 2 (a) Plan-view optical microscope image of the permeability-controlled optical modulator (upper). Oblique view of TGMs for MZ arms, observed with SEM (lower). (b) Transmission characteristics of the device as a function of gate bias, measured for 1550-nm TE-polarized light. (c) Transmission intensity change of the device as a function of an interaction distance of the TGM, calculated by finite difference methods.

1(b) lower). After that, a 100-nm thick SiO_2 layer was formed on the surface with plasma-enhanced chemical vapor deposition.

Figure 1(c) shows transmission spectra of a 300×300-nm TGM array, measured with a Fourier-transform infrared spectrometer (FTIR). It also shows simulated transmission spectra of a sample having almost the same structure as that of experimental one, for an incident light normal to the TGM plane (same as FTIR measurement) and parallel to the TGM plane (same as an actual device measurement). For an incident light normal to the TGM plane, the electromagnetic field cannot magnetically couple to the TGM, leaving only the Mie resonance of the TGM at around 230 THz, which is consistent with what we observed in the experiment. In contrast, for an incident light parallel to the TGM plane, two transmission minima for both of the *LC* and Mie resonances are observed at 185 and 230 THz, respectively. This means the incident light can magnetically couple to the TGM in an actual device, leading to the pronounced magnetic response (non-unity permeability) at optical communication range.

3. Permeability-controlled optical modulator using TGM

On the basis of the results in the previous section, we fabricated permeability-controlled optical modulator. The fabrication process is as follows. An InGaAsP core layer (λ_g = 1.22 μm, 200-nm thick), an *n*-InP cladding layer (350-nm thick), and a GaInAs fin channel layer (50-nm thick) were grown on a (100) oriented *n*-InP substrate in this order with metal-organic vapor phase epitaxy. On the surface of the initial wafer, MZI patterns were formed with EBL after fabricating TGM array in the same way mentioned above. Electrodes were deposited on both the upper SiO_2 gate dielectric and bottom *n*-InP cladding sections.

Figure 2(a) shows the plan-view optical microscope image of the MZI-based permeability-controlled optical modulator. The length of the TGM array along the arm was set to 200 μm. Here, on one side of the arms, we formed pseudo-TGM structure having similar appearance but materially different from the real TGM. The pseudo-TGM structure consists of a metal resonator with the different number of cuts compared to the real TGM as shown in Fig. 2(a). This structure has identical permittivity of the real TGM but a resonant frequency is far from optical communication band (<100 THz). Thus, the phase difference generated between the two arms is dependent only on permeability change of the TGM array. Figure 2(b) shows transmission characteristics of the device as a function of gate bias, measured for 1550-nm TE mode. In this work three different TGM sizes were prepared: 400×400 nm, 350×350 nm and 300×300 nm. Only for the device with 300×300-nm TGMs, an extinction ratio of 6.9 dB was obtained and a voltage for switching the modulator was in the range of 2.0 to 12.0 V. The TGM-size-dependent transmission characteristics are consistent with the results shown in the previous section. In addition, we calculated transmission characteristics of the device by considering the TGM array as one averaging layer. In simulation, constitutive parameters (permittivity and permeability) of a TGM averaged layer were first retrieved from S-parameters, with the use of the full-wave calculation. Here, a thickness of the averaged layer (i.e. magnetic interaction distance) was changed from 300 to 700 nm. After that, transmission characteristics of the modulator were calculated by the eigenmode expansion method. Figure 2(c) shows transmission intensity change of the modulator under a gate bias as a function of a magnetic interaction distance of the TGM layer. Compared this result with experimental results mentioned before, the magnetic interaction distance was estimated to be 600 nm, at that time the real part of the permeability of the TGM layer was changed from 0.63 to 0.7 under a gate bias.

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