Metamaterial-based Control of Permeability in GaInAsP/InP Multimode-Interferometers

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***Abstract*—We proposed and fabricated an InP-based waveguide MMI device combined with a layer consisting of split-ring resonator array. Magnetic interaction between the metamaterial and propagating light in the MMI was demonstrated at optical frequency.**

I. Introduction

The relative permeability of every natural material is 1 at optical frequency because the macroscopic magnetization of natural materials cannot follow the ac magnetic field of light. If we can break this restriction, we will be able to open a new field in optical-communication device technology. To move one step closer to this goal, we demonstrate that the permeability of InP-based multimode-interferometers (MMIs) can be controlled using metameterials [1, 2].

Metamaterials have recently attracted strong interest because they can materialize 'non-unity' permeability and thereby providing the possibility of slowing, trapping and releasing light signals in optical slab waveguides [3, 4]. Applying the concept of metamaterials to actual devices will produce advanced optical-communication devices with novel operation principles, which we call *metaphotonics*.

To open up the field of *metaphotonics*, we are developing photonic devices consisting of semiconductor optical wavegudes and metamaterial layers. To examine the feasibility of waveguide-based metamaterial devices, we fabricated a 1.5-µm-band, MMI coupler with a metamaterial layer, and observed magnetic interaction between the metamaterial and propagating light in the MMI. The following sections provide the outline of our results.

II. Principle and Simulation Analysis

Figure 1 shows our metamaterial MMI device consisting of a GaInAsP/InP optical waveguide coupler and a gold split-ring-resonator (SRR) array attached on the coupler. An 1×1 MMI is shown as an example. If input TE-mode light has a frequency equal to SRR resonance frequency, the SRR array region operates as a metamaterial layer. That is, the real part of the relative permeability of the SRR array region changes from 1 because of the magnetic interaction between the SRR and light in the MMI. Under this condition, the imaginary part of the permeability is not 0 and has a large absolute value.

We calculated the real and imaginary parts of the SRR array region. We first estimated the magnetic responses of the gold SRRs in optical frequency region, using the Biot-Savart's law and the field averaging theory (see [5] for this theory). The SRR is a gold square ring with four gaps (see inset of Fig. 2) placed in a host material with a relative permittivity of ε_r=2.25 (e.g., glass). Figure 2 shows the result, that is, the real and imaginary parts of the permeability as a function of frequency of light, for various SRR sizes L (where W_1 and W_2 were kept constant). Thickness of the SRR was the same as the penetration depth of gold at each frequency. As the dimensions of the SRR decreases, the resonant frequency shifts to a higher value and the SRRs with L = 350-400 nm show magnetic response at 1.5-µm-band frequencies (around 193 THz).

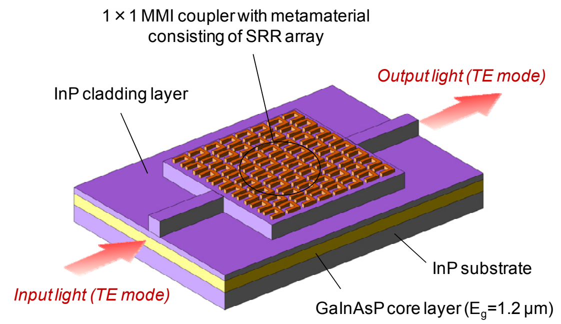

Fig. 1. Waveguide-based multimode-interferometer (GaInAsP/InP 1×1 MMI) and metamaterial region (gold SRR array) attached on the waveguide.

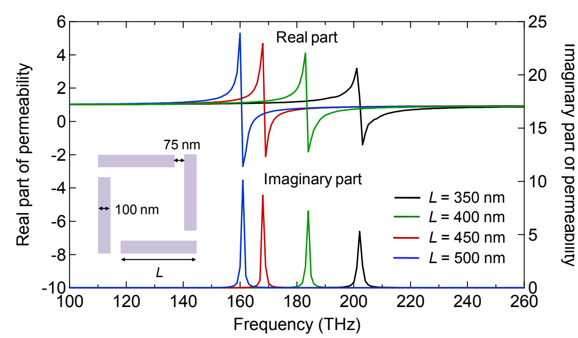

Fig. 2. Real and imaginary parts of permeability of gold SRRs in glass (ε_r=2.25) as a function of frequency, with SRR size L as a parameter (W_1 = W_2 = 100 nm).

III. Fabrication and Measurement Results

We fabricated the MMI device for use at 1.5-µm wavelength and confirmed the magnetic interaction between the metamaterial region and light in the MMI. The fabrication process is as follows. An undoped GaInAsP core layer (λ_g = 1.2 µm, 200-nm thick) and an undoped InP cladding layer (450-nm thick) were grown on a (100) oriented semi-insulating InP

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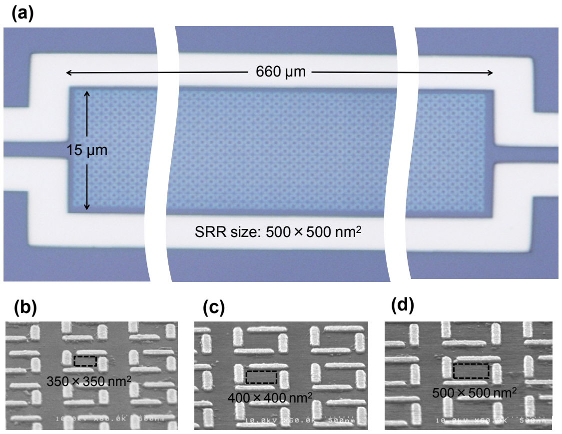

Fig. 3. (a) Optical microscope image of 1×1 MMI with metamaterial consisting of 500×500 nm^2 gold SRR array. (b-d) SEM images of 4-cut SRR arrays with different sizes.

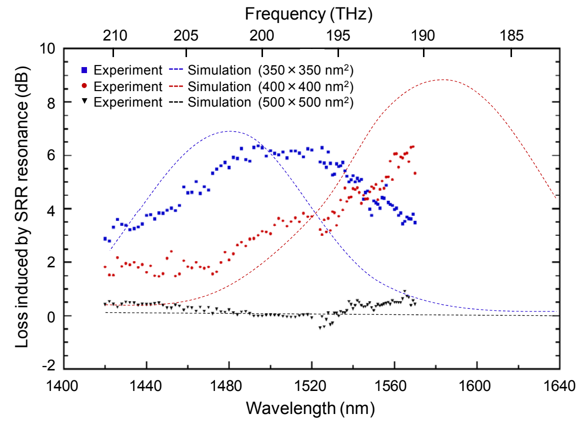

Fig. 4. Experimental propagation loss in devices with 350×350 nm^2 SRRs (blue dots), with 400×400 nm^2 SRRs (red dots), and with 500×500 nm^2 SRRs (black dots) as a function of wavelength from 1420 to 1570 nm, measured for TE-mode light. Simulation result is also plotted for each device (dashed lines).

substrate in this order with organno-metallic vapor phase epitaxy. On the surface of the cladding layer, a SRR array consisting of a 5-nm thick Ti and a 20-nm thick Au was formed using electron-beam (EB) lithography and lift-off process. After that, to fabricate the 1×1 MMI coupler, a SiO_2 mask (100-nm thick) was formed with plasma-enhanced chemical vapor deposition and EB lithography, and then CH_4/H_2 reactive-ion-etching was carried out. The width and length of the MMI were set to 15 and 650 µm. Figure 3 shows optical microscope image of the device with 500×500 nm^2 gold SRR array and SEM images of *4-cut* SRR arrays with different sizes (350×350, 400×400, and 500×500 nm^2).

In addition to these experimental samples, we also made control samples with SRRs consisting of *2-cut* gold square rings with the same size as that of the *4-cut* SRR. The *2-cut* SRR has a resonant frequency of 120 THz, far from 193 THz, so it does not interact with 1.5-µm light.

To examine the magnetic interaction between SRRs and light traveling in the MMI, we measured the transmission loss of light in the device. As shown in Fig. 2, the magnetic interaction produces the large imaginary part of the permeability. This causes an absorption loss of light in the device, so we can know the occurrence of the interaction by measuring the propagation loss in the device.

In the measurement, light from a tunable laser was sent to the device through a polarization controller. To clarify the effect of the magnetic interaction, we took the difference between the transmission intensity for the experimantal samples (with *4-cut* SRRs) and that for the control samples (with *2-cut* SRRs). This difference shows an intrinsic loss induced by SRR resonance without including the loss caused by other factors (such as ohmic loss in gold, lensed-fiber coupling loss, and wavelength-dependent propagation loss in the MMI). Figure 4 plots the measured intrinsic loss in devices with 350×350 nm^2 SRRs (blue dots), devices with 400×400 nm^2 SRRs (red dots), and devices with 500×500 nm^2 SRRs (black dots) as a function of wavelength from 1420 to 1575 nm, measured for incident light of TE-mode light. Simulation result (calculated with the transfer-matrix method and Fourier expansion method) is also plotted for each device (dashed lines). The magnetic interaction was observed in the device with 350×350 nm^2 SRRs at 1.5-µm wavelength; that is, the intrinsic loss induced by SRR resonance showed a peak at the wavelength of 1500 nm (blue dots in Fig. 4). As the size of SRRs increased (i.e., 400×400 nm^2), the peak shifted towards a longer wavelength and was out of this measurement range. For the device with 500×500 nm^2 SRRs, the loss induced by SRR resonance was almost 0 at this wavelength range. This wavelength- and SRR-size-dependent absorption shows that the magnetic field of light interacted with the SRRs to produce magnetic resonance at optical frequency.

IV. Conclusion

We proposed and fabricated an InP-based MMI device combined with SRR-based metamaterial. The transmission characteristics of the device strongly depended on the wavelength of input light. This means that the metamaterial region interacted with the magnetic field of propagating light and produced magnetic resonance at optical frequencies. Our result is a first demonstration of a combination of compound-semiconductor-based photonic devices and metamaterials.

Acknowledgment

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