

# Magnetic Interaction at Optical Frequencies in InP-based Waveguide Device Combined with Metamaterial

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**Abstract:** We developed a waveguide optical device combined with left-handed materials consisting of minute split-ring resonators. The device can operate as a 1.5- $\mu\text{m}$ -band all-optical switch, making use of magnetic resonance between the resonators and light.

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**OCIS codes:** (230.3120) Integrated optics device; (999.9999) Meta-materials; (160.4760) Optical properties.

## 1 Left-handed materials for optical devices

One promising way of creating novel optical-communication devices is controlling the *permeability*, as well as the permittivity, of materials that form the devices. This can be achieved using the concept of left-handed materials (LHMs), or meta-materials, which have attracted growing attention in recent years [1-3]. To examine the feasibility of such LHM optical devices, we designed and realized a 1.5- $\mu\text{m}$ -band, all-optical switch consisting of a semiconductor waveguide with a LHM region and confirmed magnetic interaction between the LHM and light that traveled in the waveguide. The following provides the outline of the device and the experimental results.

## 2 Optical switch based on the dynamics of LHMs----device design and simulation

Figure 1 shows our waveguide-based optical on/off switch. The device is composed of a GaInAsP/InP  $1 \times 1$  multimode-interferometer (MMI) coupler and a LHM region consisting of gold split-ring resonator (SRR) array attached on the coupler. For input TE light with a frequency equal to SRR resonance frequency, the imaginary part of the permeability of the LHM has a large absolute value, and this causes a large propagation loss of the light in the MMI coupler. If we apply controlling light ( $\lambda < \lambda_{g, \text{InP}}$ ) to the LHM, as shown in the figure, a gap of each SRR is short-circuited by excited carriers, and consequently the magnetic response of the LHM vanishes. This decreases the imaginary part of the LHM permeability to 0, thereby decreasing the propagation loss of the light. In this way, the input light can be switched directly by the controlling light.

To make the LHM region, we used a single SRR (s-SRR) consisting of a metal ring divided into four because a small geometrical capacitance of the s-SRR effectively realizes a high-resonant frequency [4]. We analyzed the magnetic response of the gold s-SRR, using the Biot-Savart law and the field averaging theory (see [5] for this theory). Figure 2 shows the results for the real and imaginary parts of the s-SRR, with its size as a parameter. Using these results, we calculated the propagation loss of light in the MMI. Figure 3 shows the result plotted as a function of wavelength with/without the magnetic response of s-SRRs. A change in propagation loss (extinction ratio) of 4.2 dB or larger can be expected at 1560-1570 nm wavelength (corresponding to SRR resonance frequency).

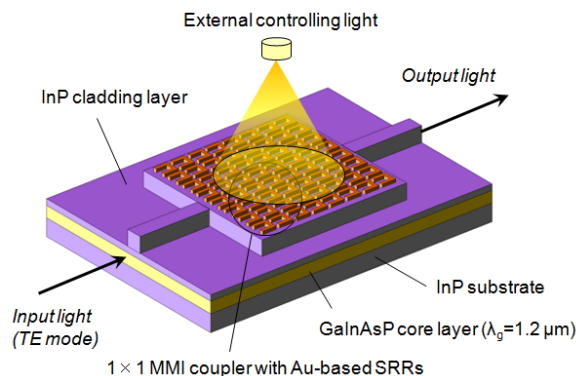


Fig 1. All-optical waveguide switching device consisting of InP-based  $1 \times 1$  MMI coupler with gold SRRs.

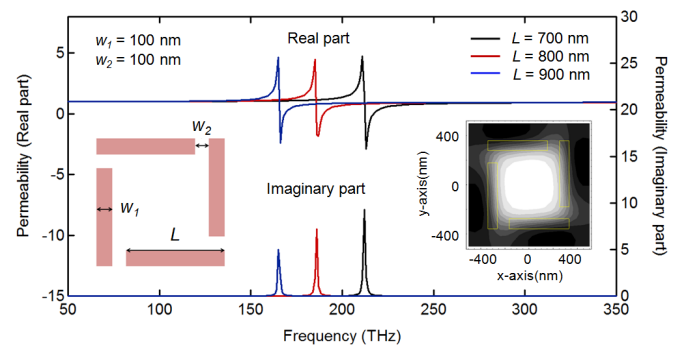


Fig 2. Real and imaginary parts of effective permeability of gold SRRs as a function of SRR dimensions. Right inset shows magnetic field density in SRR ( $r=800\text{nm}$ ) at 185 THz resonance.

### 3 Device fabrication and transmission characteristics

We fabricated an actual device as follows. A starting material was a (100) oriented semi-insulating InP substrate. An undoped GaInAsP core layer ( $\lambda_g = 1.2 \mu\text{m}$ , 200-nm thick) and an undoped InP cladding layer (500-nm thick) were grown in this order with organo-metallic vapor phase epitaxy (OMVPE). On the surface of the cladding layer, a s-SRR array consisting of a 5-nm thick Ti and a 20-nm thick Au was made using electron-beam (EB) lithography and lift-off process. After that, to make the  $1 \times 1$  MMI coupler, a  $\text{SiO}_2$  mask (100-nm thick) was formed with plasma-enhanced chemical vapor deposition (PECVD) and EB lithography, and then  $\text{CH}_4/\text{H}_2$  reactive-ion-etching was carried out. Figure 4 shows the plan view and the cross sections of the device.

To examine the interaction of the SRRs and light traveling in the MMI, we measured the transmission characteristics of the device. The light from a tunable laser was coupled to and out of the device through a polarization controller. In this measurement, control devices without SRRs were also prepared for comparison. Figure 5 plots the transmission for devices with SRRs (blue curves) and without SRRs (black curves) as a function of wavelength from 1524 to 1575 nm, measured for incident light of (a) TE mode and (b) TM mode. To clarify the effect of magnetic interaction between light and the SRRs, we took the difference between the transmission intensity with SRRs and that without SRRs (see red curves in Fig. 5). As can be seen, the magnetic interaction was observed only for TE-mode light; that is, the transmission intensity with SRRs gradually decreases with wavelength for TE mode, while no decrease is observed for TM mode. This polarization-dependent absorption is obvious proof that the magnetic field of light interacted with the SRRs to produce magnetic resonance at optical frequencies. (The frequency of resonance peak in this device shifted towards a longer wavelength than we had expected and was out of the measurement range because the host material for the SRRs in the experiment was  $\text{SiO}_2$  and different from material (i.e., air) assumed in simulation.)

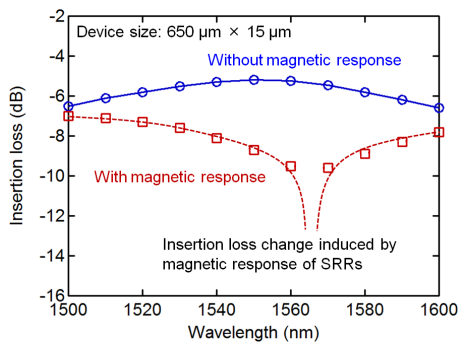


Fig 3. Calculated extinction ratio in device ( $L=750\text{nm}$ ,  $w_1=100\text{nm}$ ,  $w_2=100\text{nm}$ ) as a function of wavelength.

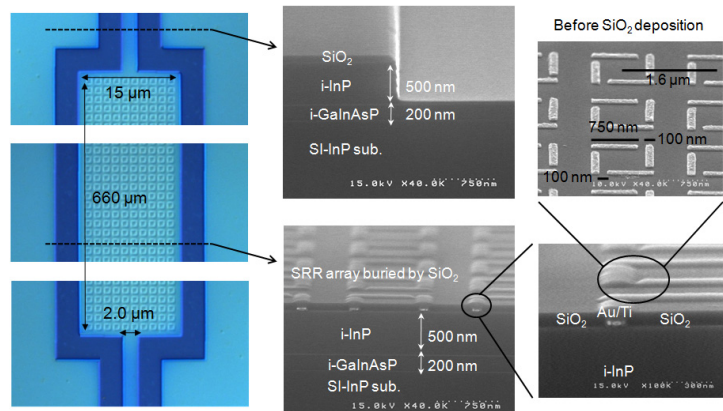


Fig 4. Optical microscope image (left) and SEM cross section image (middle and right) of fabricated  $1 \times 1$  MMI coupler with gold SRRs covered with  $\text{SiO}_2$  layer.

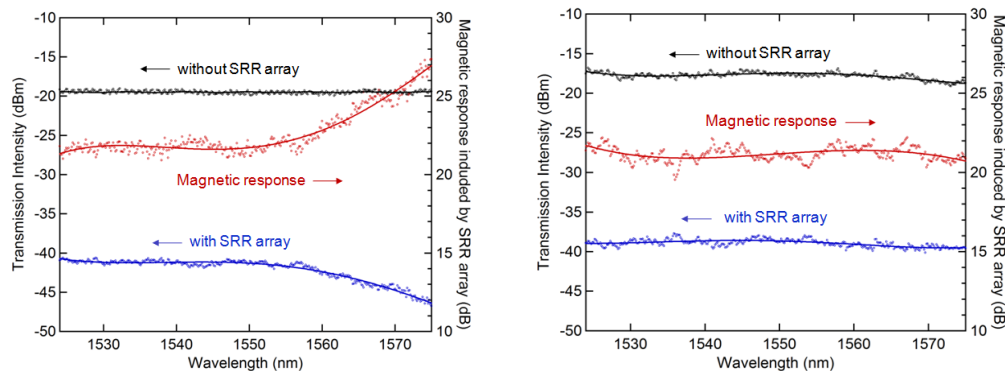


Fig 5. Transmission intensity of devices with SRR (blue lines) and without SRRs (black lines) as a function of wavelength from 1524 to 1575 nm, measured for (a) TE mode and (b) TM mode. Difference between device with SRRs and device without SRRs is also plotted for both modes (red lines). Difference with SRRs for TE mode increases with wavelength because of magnetic interaction of light and SRRs.

### References

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