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## Effects of Exciton-polariton on Mach-zehnder Interference Devices

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**Abstract:** A new optoelectronic device based on excitonpolariton was studied. In particular a Mach-Zehnder interference device fabricated by using a GaAs quantum well was studied. We simulated the output characteristics of Mach-Zehnder interference device by using a Finite Difference Time Domain (FDTD) method. Then we compared them with the experimental results measured in a low-temperature. After that we obtained the numerical values of electro-optic effect coefficients. Those were as large as  $105 \times 10^{-11}$  m/V for 4.5 K, while  $74 \times 10^{-11}$  m/V for 77 K. Therefore this estimation is considerably large, showing 57 (4 K) and 41 (77 K) times larger than conventional KDP crystal. This effect is probably caused by the excitonpolariton effect. Furthermore, we performed a photocurrent experiment to understand the transmitted light phase change characteristics, causing such large electro-optics effect at a comparatively higher temperature. Temperature dependence of photocurrent showed that the absorption edge and exciton peak remained constant up to 77 K, and then shifted to lower energy as the temperature increased. This probably explains how the large electro-optic effect can be obtained at a comparatively high temperature, i.e., 77 K.

**Keywords:** Electro-optic effect coefficient, Finite Difference Time Domain (FDTD), photocurrent, quantum well waveguide

### INTRODUCTION

Optical communication systems utilize optical devices to modulate, to transmit and to process optical signal. Rapid development of the information society has led to an increase in the speed of data transfer. Therefore, it becomes inevitable to develop the optical devices to increase bandwidth, to increase the response and to minimize the system size (Ismail *et al.*, 2014; Latiff *et al.*, 2013; Chuang, 1999).

In order to realize such devices, we examined the basic characteristics of the Mach-Zehnder (MZ) type interference device. The MZ type interference device can be used as an optical modulator in an optical communication system (Cvijetic, 2004). Our device, the MZ interference device with a multiple quantum well waveguide can be a promising candidate for an ultrafast modulator due to excitonicpolariton effect (Tada *et al.*, 2005; Katsuyama and Ogawa, 1994; Jeffrey and Ashley, 1994). The concept of excitonicpolariton was introduced by Pekar (1958), Hopfield (1958) and Hopfield and Thomas (1963). An excitonpolariton is a composite quasi-particle formed by coupling of an exciton and photon. One of the most significant inherent features of excitonicpolariton is high sensitivity to an electric field (Liew *et al.*, 2010; Hosomi *et al.*, 1999).

In this research, we analyzed the characteristics of MZ interference device fabricated by using a GaAs quantum well. We performed a numerical simulation using a Finite Difference Time Domain (FDTD) method to understand the propagating light. Then we compared the simulation results with the experimental results and calculated the electro-optic effect. We also measured photocurrent of the device to understand the phase shift relating to the interference effect (Steger *et al.*, 2012).

### MATERIALS AND METHODS

**Sample structure:** Figure 1 shows a schematic illustration of the MZ interference device, which

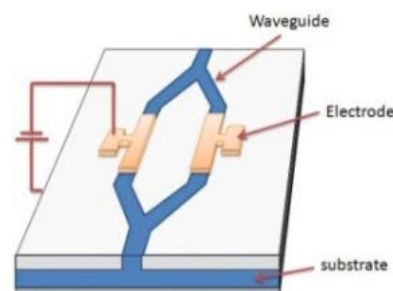


Fig. 1: Schematic illustration of the sample

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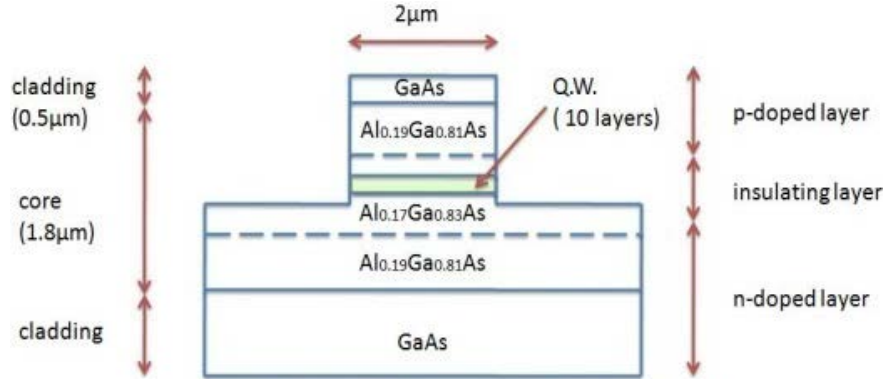


Fig. 2: Layer structure of the quantum well waveguide

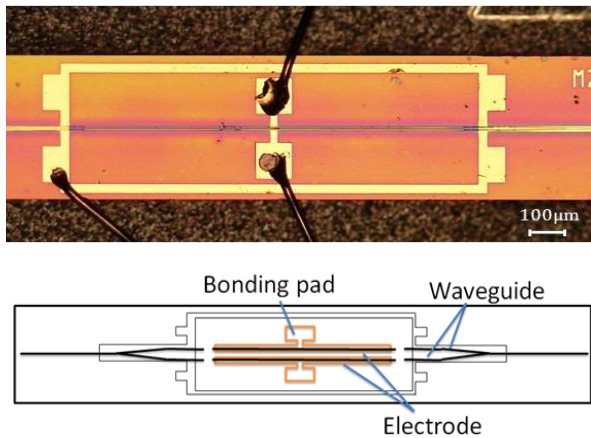


Fig. 3: Mach-zehnder interference device

consists of a 2 μm-wide GaAs/AlGaAs single-mode waveguide and a 1.06 mm-long electrode for applying

the electric field. The cross-sectional structure of the wave guide (Fig. 2) which is made of p-i-n GaAs/AlGaAs layers. A 1.8 μm-thick  $Al_{0.13}Ga_{0.87}As$  core layer is sandwiched between  $Al_{0.17}Ga_{0.83}As$  cladding layers. At the center of the core layer, ten layers of 7.5 nm GaAs/ $Al_{0.3}Ga_{0.7}As$  Quantum Wells (QWs) are formed. The resonance wave length of the quantum well is 803 nm at 4.5 K. The total length of the device is 2.45 mm. Figure 3 is a microscopic image of the actual device, which has the shielding electrodes that are necessary for stable operation (Katsuyama and Hosomi, 2002).

**Experimental measurement system:** The optical measurement setup is schematically Fig. 4 where tunable Ti-sapphire laser, excited by an Ar laser, was used as a light source. The tunable range of the Ti-sapphire laser was 770-870 nm and the power for this measurement was fixed to 10 mW. The Ti-sapphire laser beam was transmitted with conventional optics

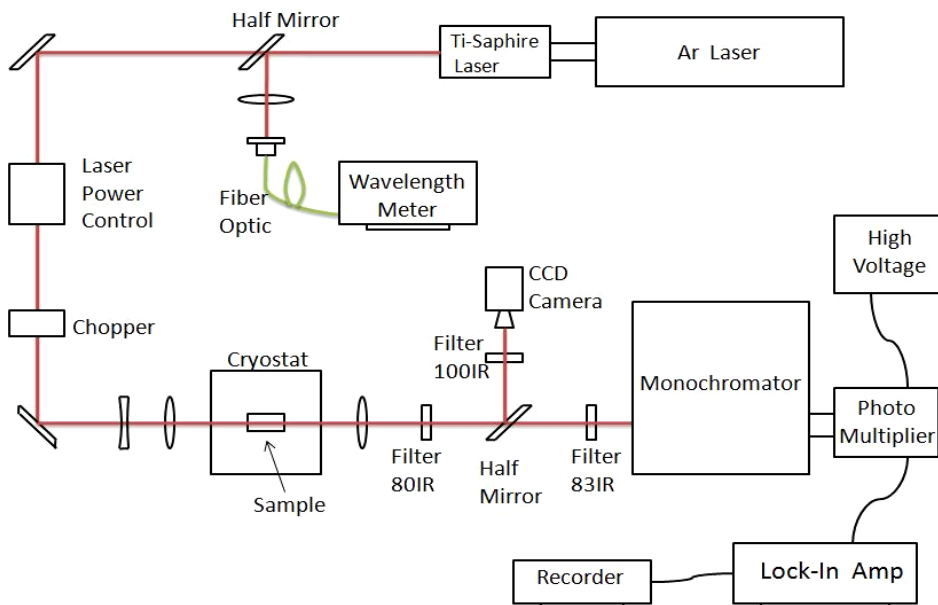


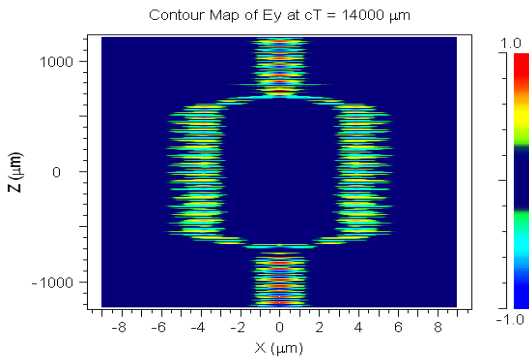
Fig. 4: Measurement setup

and focused on the end of the Mach-Zehnder interference device in the cryostat. After that the transmitted beam entered the monochromator and the output was then measured by the lock-in-amp. The transmitted beam was also observed by a CCD camera. Reverse bias voltage was applied to the sample with the wire connected to the sample in the cryostat (Nizamuddin *et al.*, 2009).

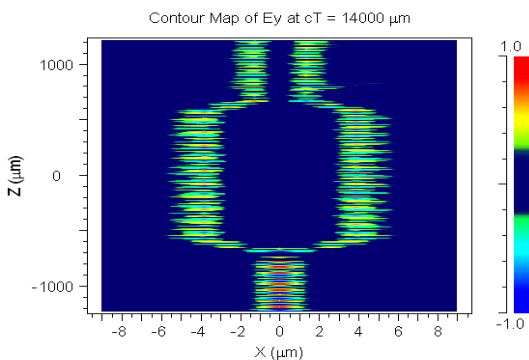
## RESULTS AND DISCUSSION

**Simulation results:** In the simulation, refractive index was changed in one side of the waveguides in every simulation by adding 0.00025 refractive index difference  $\Delta n$ . Then the output light intensity was observed at the end of the waveguide. The typical simulation results are shown in Fig. 5. As shown in Fig. 5a, the refractive index difference  $\Delta n$  was zero and then the output was maximum. While in Fig. 5b, when the refractive index difference was 0.000353, the propagating light was perfectly radiated from the waveguide and the output intensity became zero.

The simulation result was then plotted Fig. 6, showing the relation between the normalized output power and the index difference between two arms of the waveguides. The result showed the first minimum



(a) Index difference  $\Delta n = 0$



(b) Index difference  $\Delta n = 0.000353$

Fig. 5: Simulation of light transmission in the sample

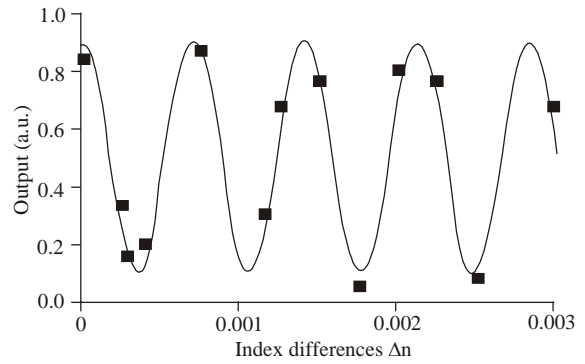


Fig. 6: Refractive index difference vs. output

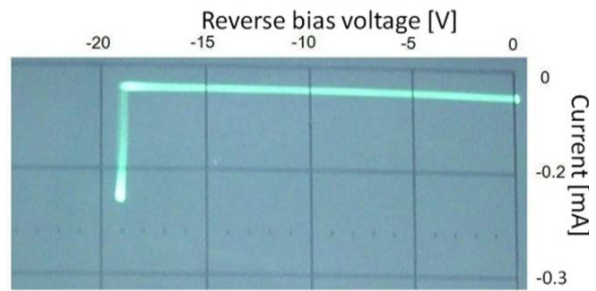


Fig. 7: Voltage vs. current

output was observed when the refractive index difference  $\Delta n$  was 0.000353. That means the light wave had shifted its phase by  $\pi$  rad.

**Experimental results:** Figure 7 shows the reverse bias characteristic of the sample. The break down voltage was -19 V, showing that the sufficient electric field can be applied to the quantum well layer.

By using these samples, we measured the light transmission characteristics and compared the measured results with simulation. Figure 8 shows the voltage dependence of the output for the sample at 4.5 and 77 K (Katsuyama and Hosomi, 2003). Results showed the voltage, giving the first minimum output power, was 0.7 V for 4.5 K and 1.1 V for 77 K. Therefore, these values corresponded to the refractive index difference  $\Delta n = 0.000353$  which was obtained by the above simulation.

However,  $\Delta n = 0.000353$  means the average value for the waveguide. Since the refractive index change occurred only in the quantum well layer, the refractive index change in the quantum well reached as large as 0.0040. This is because the quantum well layer occupies 8.8% of the whole light field. Therefore, in 4.5 K, we obtained  $105 \times 10^{-11}$  m/V for quantum well, while in 77 K,  $74 \times 10^{-11}$  m/V. These values are much higher than that of typical electro-optic material such as KDP crystal (Potassium Dihydrogen Phosphate) with  $1.82 \times 10^{-11}$  m/V.

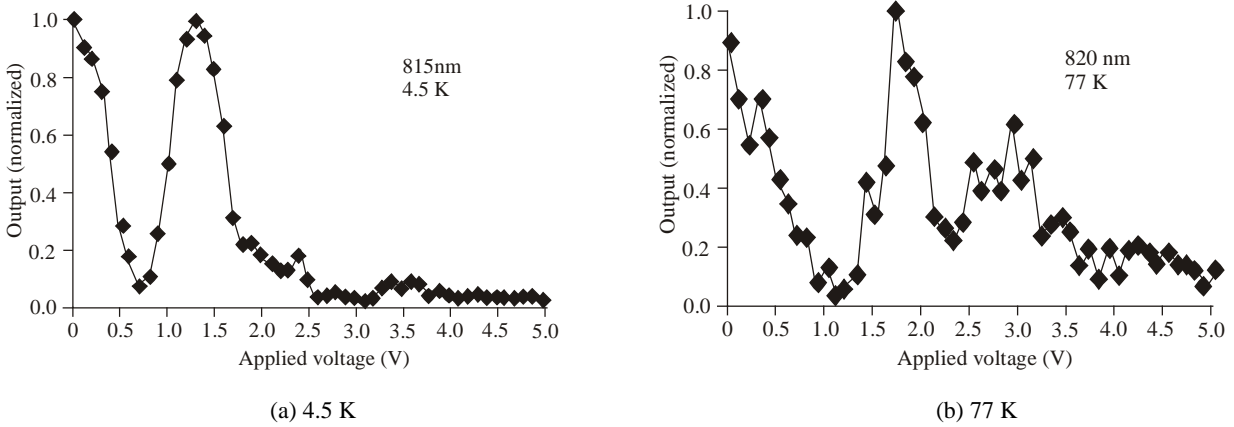


Fig. 8: Voltage dependence of the output

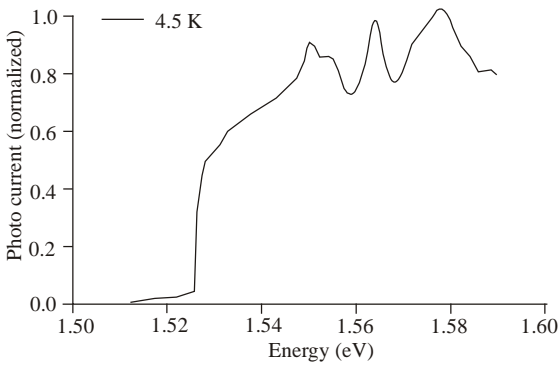


Fig. 9: Photocurrent result at 4.5 K

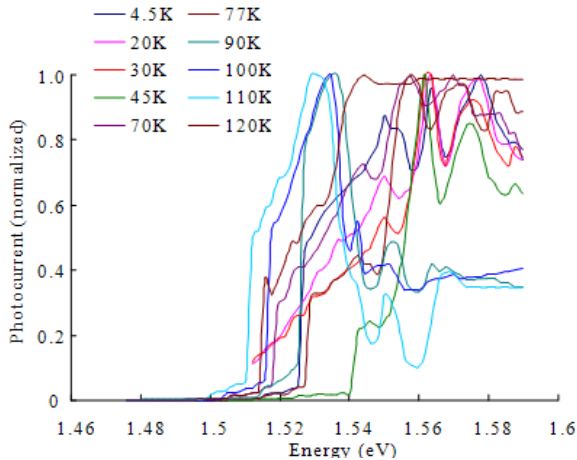


Fig. 10: Photocurrent results

At a comparatively higher temperature (77 K), the phase shift operation was still stable, also still giving a high electro-optic effect. In order to clarify the phenomena of this phase shift, we measured temperature dependence of the photocurrent. As the photocurrent is related to the absorption coefficient, we can get a clue to understand the refractive index change. Photo current was measured by applying the reverse

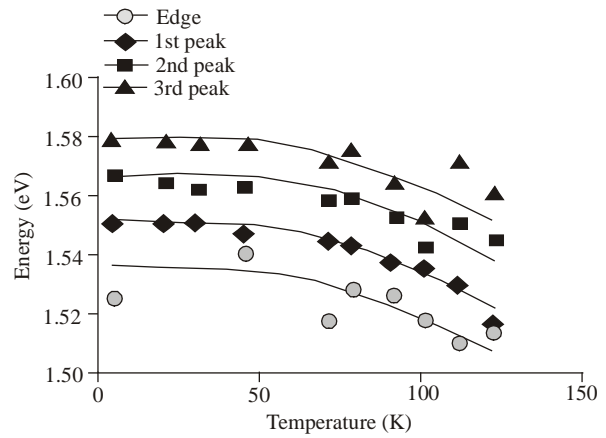


Fig. 11: Edge and peak values of photocurrent spectra

bias-2 V to the electrode at temperature from 4 to 120 K.

Figure 9 shows the photocurrent spectrum at 4.5 K. Slope edge can be found at about 1.52 eV and 1<sup>st</sup> peak is 1.55 eV. This 1<sup>st</sup> peak is probably related to the exciton absorption energy. At a higher energy region there are 2<sup>nd</sup> and 3<sup>rd</sup> peaks. Figure 10 shows the temperature dependence of photocurrent spectra. The photocurrent was normalized in this case. The result shows that the photocurrent spectrum edge and peaks move to lower energy region as the temperature increases.

Figure 11 shows the temperature dependence of the edge value, 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> peak values. It was found that each peak energy remained constant up to 50 K then shifted to lower energy. These photocurrent behavior means that the absorption coefficient should not be change much up to near 77 K. As a result, we expect that the refractive index would also be stable up to near 77 K. This probably gives the reason why we can still get a large refractive index change at the comparatively high temperature, i.e., 77 K.

## CONCLUSION

We performed the analysis of the characteristics of Mach-Zehnder interference device, which has at the center of the core layer of the device, ten layers of 7.5 nm GaAs/Al<sub>0.3</sub>Ga<sub>0.7</sub>As quantum wells. The simulation result showed that the minimum output was observed when the refractive index difference was 0.000353. Compared with the experimental result there refractive index change of the sample reached as large as  $105 \times 10^{-11}$  m/V for 4.5 K, while  $74 \times 10^{-11}$  m/V for 77 K. Therefore this estimation is considerably large, showing 57 (4 K) and 41 (77 K) times larger than conventional KDP crystal. This effect was probably caused by the excitonicpolariton effect. It is noticeable that at a comparatively higher temperature (77 K) phase shift operation still remained efficient. In order to understand how excitonpolariton affected the phase shift in our device we measured the temperature dependence of photocurrent. The result showed that exciton transition energy peaks and edges of photocurrent spectra remained constant up to near 77 K, and then shifted to lower energy. This probably explains how the phase shift operation still remained efficient at the comparatively high temperature (77 K).

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