Waveguide-Type All Optical Switch Using Saturable Absorption of Graphene

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Abstract— **In photonic routing nodes, pico-second switching will be a key function. We propose an all optical switch consisting of two-stage Mach-Zehnder interferometers, whose arms contain graphene saturable absorber films. The switching characteristics are theoretically analyzed and numerically simulated by FD-BPM.**

Keywords-component; optical switch; saturable absorption; graphene; asymmetric X-junction coupler

I. INTRODUCTION

Pico-second optical switching devices are required in photonic switching nodes. The authors have studied on all-optical wavelength-selective switches, where switching is controlled by amplifying the optical guided wave with Raman amplifiers placed in the waveguides of the switch.[1,2] The switch, however, requires waveguide-type efficient crystalline Raman amplifiers. In this report, we propose introducing graphene films for controlling the optical amplitudes with the similar switch architecture. We discuss the switching characteristics using a reported experimental result on saturable absorption by Bao et al.[3] Complete switching can be achieved by controlling the optical wave using nonlinear saturable absorption. The switching characteristics are verified by FD-BPM simulation.

II. MODELING OF GRAPHENE ABSORPTION

In the proposed switch, the amplitude of an optical signal is controlled by a control light. First, we consider a model of optical nonlinearity of a monolayer graphene as illustrated in Fig.1.[3] Although this saturable absorption is observed for an optical input by changing the incident intensity, we consider the incident light is sum of a weak signal light and an intense control light, where the polarization or wavelength of these two lights are assumed to be different.

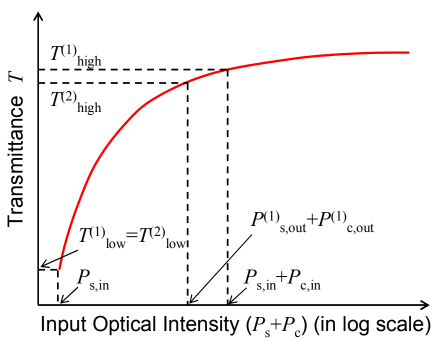

Fig.1 Saturable absorption in graphene

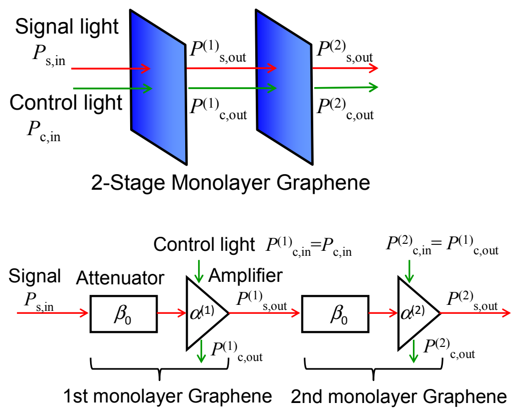

Fig.2 Modeling of two-stage graphene

A model for two-stage monolayer graphene is shown in Fig.2. Although absorption is increased for the signal light more than that for a single graphene, the amplitude of the optical signal can be controlled with a wider range. When the incident light is weak $P_{s,in}$ and without control light, the transmittance of the first graphene is low $T^{(1)}_{low}$. The transmission coefficient for the optical amplitude is given by $t^{(1)}_{low}=(T^{(1)}_{low})^{1/2}=\beta_0$. By increasing the incident light intensity $P_{s,in}+P_{c,in}$ including control light, the transmittance increases to $T^{(1)}_{high}$. The transmission coefficient is given by $t^{(1)}_{high}=(T^{(1)}_{high})^{1/2}=\beta_0\alpha^{(1)}$. For the second grapheme, the control light is attenuated to $P^{(1)}_{c,out}=\beta_0\alpha^{(1)}P_{c,in}$ through the first graphene. The transmittance of the second graphene is decreased to $T^{(2)}_{high}$. Then, the transmission coefficient of the second graphene is $t^{(2)}_{high}=(T^{(2)}_{high})^{1/2}=\beta_0\alpha^{(2)}$.

From the experimental result [3], we find β_0=0.556 (=$0.309^{1/2}$). for $P_{s,in}$<3mW/μm^2, and $\beta_0\alpha^{(1)}$=0.894 (=$0.8^{1/2}$) for $P_{s,in}+P_{c,in}$=10mW/μm^2. Then, $\alpha^{(1)}$=1.608 is obtained. For the second graphene, we find $\beta_0\alpha^{(2)}$=0.866 (=$0.75^{1/2}$) for $P^{(1)}_{s,out}+P^{(1)}_{c,out}$=8mW/μm^2. Then $\alpha^{(2)}$=1.558 is obtained.

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III. OPTICAL SWITCH ARCHITECTURE

A proposed optical switch is illustrated in Fig.3. The device consists of two cascaded interferometers whose couplers are asymmetric X-junction couplers. Two-stage graphene films are inserted in the two waveguides of the first interferometer. The graphene films in arm A or B is modeled by an attenuator having amplitude attenuation coefficient β_0^2 and an amplifier having amplitude amplification coefficient of $\alpha_i = \alpha_i^{(1)}\alpha_i^{(2)}$, i=A or B. A fixed attenuator $\beta_{\rm fix}$ is employed in one arm of the second interferometer.

The output fields through the switch are related to the input fields as

$$\begin{pmatrix} A_{out} \\ B_{out} \end{pmatrix} = \left(\frac{1}{\sqrt{2}}\right)^3 \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \beta_{fix} \end{pmatrix} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \times \begin{pmatrix} \beta_0^2\alpha_B & 0 \\ 0 & \beta_0^2\alpha_A \end{pmatrix} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} A_{in} \\ B_{in} \end{pmatrix} = \frac{\beta_0^2}{2\sqrt{2}} \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} A_{in} \\ B_{in} \end{pmatrix} \quad (1)$$

where

$$\begin{cases} a_{11} = \alpha_A - \alpha_B - \beta_{fix}(\alpha_A + \alpha_B) \\ a_{12} = \alpha_A + \alpha_B + \beta_{fix}(-\alpha_A + \alpha_B) \\ a_{21} = -(\alpha_A - \alpha_B) - \beta_{fix}(\alpha_A + \alpha_B) \\ a_{22} = -(\alpha_A + \alpha_B) + \beta_{fix}(-\alpha_A + \alpha_B) \end{cases} . \quad (2)$$

When optical signal is incident only at one input port as $A_{\rm in}=E_{\rm in}$ and $B_{\rm in}=0$, (1) becomes

$$\begin{pmatrix} A_{out} \\ B_{out} \end{pmatrix} = \frac{\beta_0^2 E_{in}}{2\sqrt{2}} \begin{pmatrix} a_{11} \\ a_{21} \end{pmatrix}. \quad (3)$$

From this equation, we find the conditions for switching as follows:

(i) When $\alpha_{\rm A}=1$, $\alpha_{\rm B}=1+2^{1/2}$ and $\beta_{\rm fix}=1/(1+2^{1/2})$,
$A_{\rm out}=-\beta_0^2 E_{\rm in}$, $B_{\rm out}=0$,

(ii) When $\alpha_{\rm A}=1+2^{1/2}$, $\alpha_{\rm B}=1$ and $\beta_{\rm fix}=1/(1+2^{1/2})$,
$A_{\rm out}=0$, $B_{\rm out}=-\beta_0^2 E_{\rm in}$.

Therefore, amplification of the amplitude coefficient of 2.414 is required for switching. The two-stage graphene films can provide $\alpha_i=\alpha_i^{(1)}\alpha_i^{(2)}$=2.505 from Section III. A control power of 10mW/μm^2 is considered to be a little too large for switching. Although the switching is accompanied by an insertion loss of β_0^2, complete switching can be achieved.

IV. FD-BPM SIMULATION

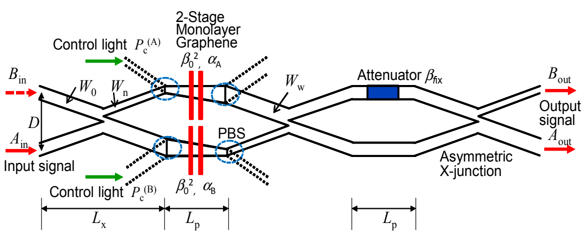

Fig.3 Switch architecture containing graphene films.

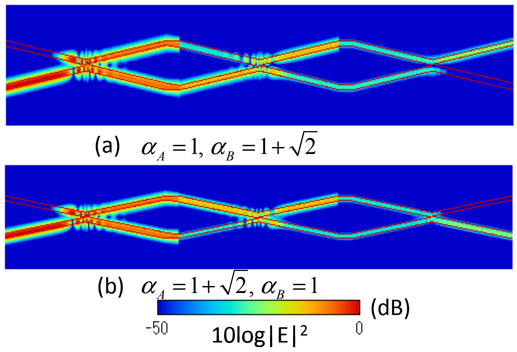

Fig.4 Simulation results of switching.

The switching operation is numerically simulated by FD-BPM. We consider two-dimensional slab waveguide model. The core and cladding regions have refractive indices of $n_{\rm c}$ = 1.461 and $n_{\rm s}$ = 1.45, respectively. The waveguide widths of the fundamental, narrow and wide waveguides of the asymmetric X-junctions are W_1 = 3.0μm, $W_{\rm n}$ = 2.6μm and $W_{\rm w}$ = 3.4μm, respectively. Optical waves are assumed to be TE mode. The lengths of the X-junction coupler and the parallel waveguides are $L_{\rm x}$ = 16mm and $L_{\rm p}$ = 1mm, respectively. The total length is 50mm. The distance of the input ports is D= 23μm.

Table I Switched output intensities.

Control Arm	Theory		Simulation	
	$\lvert A_{\rm out}\rvert^2$	$\lvert B_{\rm out}\rvert^2$	$\lvert A_{\rm out}\rvert^2$	$\lvert B_{\rm out}\rvert^2$
B	0	9.55x10-2	3.36x10-4	9.83x10-2
A	9.55x10-2	0	8.74x10-2	3.05x10-4

The switching operation at λ = 1550nm is confirmed as shown in Fig. 4, where squared electric fields $|E|^2$ are plotted. In the simulation, amplification is equivalently simulated just by increasing the electric field by multiplying the gain coefficient α at a plane located at the end of the waveguide region for the amplifier. In a similar manner, the attenuator is modeled by multiplying the electric field by β_0 or $\beta_{\rm fix}$ at the beginning of the attenuator. The normalized output intensities are summarized in Table I.

V. CONCLUSION

An all-optical switch using saturable absorption of graphene was proposed. Since only attenuation is used in controlling the guided wave, an insertion loss of 10.2dB (β_0^2=3.09) is inevitable. However, complete switching between the two output ports can be achieved.

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