Magnetically Programmable Bistable Laser Diode With Ferromagnetic Layer

Wadim Zaets and Koji Ando

Abstract: A new design of bistable laser diode, which consists of a gain section, absorption section and non-reciprocal section, is proposed. The non-reciprocal section is made of a semiconductor optical amplifier covered by a ferromagnetic layer. The non-reciprocity of magneto-optical effect significantly modifies a photon density distribution in the laser cavity and enlarges a width of hysteresis loop of bistable laser diode. The bistability itself can be switched on or off by reversing magnetization of the ferromagnetic layer.

Index Terms — Optical bistability, magnetooptic devices, magnetooptic effects, semiconductor optical amplifiers, magnetooptic isolators, semiconductor lasers.

I. Introduction

Waveguide optical isolators made of semiconductor optical amplifiers with ferromagnetic layers have been proposed recently [1,2]. Zaets *et al.* [2] showed that semiconductor optical amplifier covered by ferromagnetic layer, which is magnetized perpendicularly to the light propagation direction and in the film plane, has different gain coefficient for opposite directions of light propagation. The difference of optical constants for opposite directions of light propagation is called as a non-reciprocal effect, which is a unique feature of magneto-optical effect. Since absorption of the light by ferromagnetic layer with such magnetization is significantly different for two opposite directions of light propagation, the gain of active layer can be adjusted so that device can be transparent in one direction and absorptive in another direction. Thus, this semiconductor amplifier with ferromagnetic layer can be used as an optical isolator and one can make a part of optical waveguide amplifier as an optical isolator simply by depositing a ferromagnetic metal on it.

In this paper we propose to use such non-reciprocal amplifier to enhance performance of bistable laser diode (LD). The bistable optical devices are attractive components for all-optical systems in which optical signal is processed directly without conversion into electrical signal. Absorptive bistability through inhomogeneous current injection in semiconductor laser was first proposed by Lasher [3]. With the integration of a saturable absorber into a laser cavity, a hysteresis loop is evident in the light output versus gain section current characteristic, with the laser switching on at higher currents than it switched off. For a current inside the bistability loop the laser diode can be switched on or off by the light through side-injection or direct injection into a cavity. Fast switching speed makes bistable laser

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W. Zaets and K. Ando are with Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568, Japan.

diode very attractive for use in optical communications networks. Applications such as all-optical wavelength conversion [4], regeneration [5], logic [6], waveform distortion compensation [7], demultiplexing [8], and clocked decision circuits [9] have all been reported successfully with bistable LD having absorbing element.

We study theoretically a three-sectional bistable laser diode in which on top of the middle section the ferromagnetic metal is deposited. We will show that this non-reciprocal section modifies photon density distribution inside the laser cavity so that the bistability loop of the LD significantly enlarges and the bistability itself can be turned on or off by reversing magnetization of the ferromagnetic layer.

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II. Theory

Figure 1 shows a schematic diagram of the bistable laser diode, which is studied in this paper. It

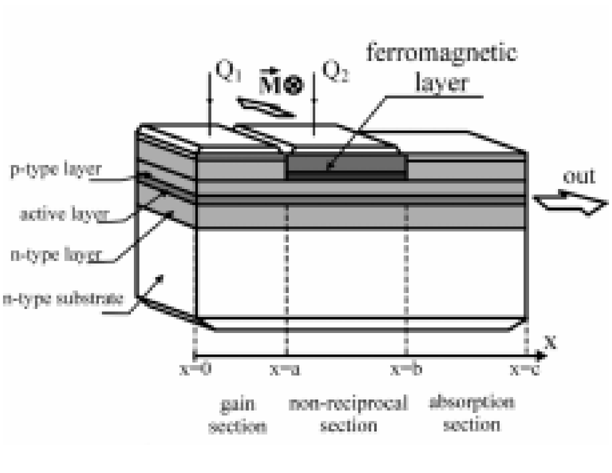

Fig.1. Schematic diagram of bistable laser diode with gain, non-reciprocal and absorption sections. In non-reciprocal section on top of optical amplifier the ferromagnetic metal is deposited. The carriers are injected into active layer in gain and non-reciprocal sections. The gain of non-reciprocal section is different for opposite directions of light propagation.

consists of three sections. All sections have common substrate, n-type buffer layer, active layer and *p*-type buffer layer. On the top of gain section there is an electrode to inject carriers into active layer. There is no electrode on top of saturable absorber section and carriers are not injected into active layer in this section. In non-reciprocal section on top of optical amplifier a ferromagnetic metal (iron, cobalt, nickel, etc.) is deposited. The ferromagnetic layer provides optical isolation and also makes *p*-contact. The carriers are injected into this section so that absorption induced by the metallic ferromagnetic layer is compensated by gain of active layer. The magnetization of ferromagnetic layer was directed perpendicularly to the light propagation in the cavity and in the film plane (as it is shown in Fig. 1). In [2] we showed that in this case the amplifier has different values of the gain in opposite directions, $k+\Delta k$ and $k-\Delta k$. Then, the photon density distribution along the non-reciprocal section can be described as

$$I_2(x) = C_1 \cdot \exp[(k+\Delta k)\cdot x] + C_2 \cdot \exp[-(k-\Delta k)\cdot x]$$

where x is coordinate along the section, C_1 and C_2 are constants. For positive values of Δk the isolation direction of non-reciprocal section is along x.

Injection rate of carrier density into the non-reciprocal section Q_2 can be adjusted so that the gain of this section in one direction can be approximately equal to its absorption in another direction, $k \approx 0$. From (1) photon density distribution along non-reciprocal section in this case is:

$$I_2(x) = A(x)\cdot \exp[\Delta k \cdot x],$$

where $A(x)$ is a function with small variation along x.

If ferromagnetic layer is magnetized so that the isolation direction is from gain to absorption sections, assuming in (2) the $A(x)$ to be a constant the photon density at both sides of non-reciprocal section can be described as

$$I_3(x=b)=\alpha\cdot I_1(x=a), \quad (3)$$

where $\alpha=\exp[\Delta k\cdot L_2]$ is the isolation ratio. I_1, I_3 are the photon density in gain and absorption sections, respectively. L_2 is the length of non-reciprocal section.

In modeling of the LD we used the approximation of constant photon flux along the gain and absorption sections. This approximation was commonly used for description of two-sectional bistable LD [10, 11]. Also, in rate equations for non-reciprocal section we used average photon density $\langle I_2\rangle$, which from (2) is

$$\langle I_2\rangle=\frac{|I_3(x=b)-I_1(x=a)|}{\ln(\alpha)} \quad (4)$$

Then, the rate equations for average photon density $\langle I_1\rangle$, $\langle I_2\rangle$, $\langle I_3\rangle$ and carrier density n_1, n_2, n_3 in gain, non-reciprocal, absorption sections can be written as

$$\begin{aligned}
dn_1/dt &= Q_1-n_1/\tau_1-B\cdot n_1^2-g_1\cdot(n_1-n_{01})\cdot\langle I_1\rangle\\
dn_2/dt &= Q_2-n_2/\tau_2-B\cdot n_2^2-g_2\cdot(n_2-n_{02})\cdot\langle I_2\rangle\\
dn_3/dt &= -n_3/\tau_3-B\cdot n_3^2-g_3\cdot(n_3-n_{03})\cdot\langle I_3\rangle\\
d\langle I_1\rangle/dt &= -\langle I_1\rangle/\tau_c+\beta\cdot B\cdot\sum_{i=1}^{3} r_i\cdot(n_i-n_{0i})^2\cdot\langle I_i\rangle/\langle I_1\rangle+\\
&+\langle I_1\rangle\cdot[r_1\cdot g_1\cdot(n_1-n_{01})+r_2\cdot(g_2\cdot(n_2-n_{02})-\gamma)+r_3\cdot g_3\cdot(n_3-n_{03})]
\end{aligned} \quad (5)$$

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where Q_i is the injection rate of carrier density, B is the radiative recombination coefficient, τ_i is the mean carrier lifetime, g_i is the differential gain, n_{0i} is the transparency carrier concentration, β is the spontaneous emission coefficient, r_i is a fraction of i-section to total length of cavity, τ_c is the lifetime of a photon, γ is the optical loss induced by the ferromagnetic layer in the non-reciprocal section. i=1, 2, 3 corresponds to gain, non-reciprocal, and absorber sections, respectively.

The equations (5) were solved under a steady-state operation condition with (3) and (4). In our calculations we assumed $GaAs_{1-x}P_x/Al_{1-x}Ga_xAs$ optical amplifier and Co ferromagnetic metal with following values of parameters [2,10]: $B=1.33\times10^{-10}\,\mathrm{cm^3s^{-1}}$, τ=5 ns, β=10^{-4}, $n_0=10^{18}\,\mathrm{cm^{-3}}$, and $g=10^{-6}\,\mathrm{cm^2s^{-1}}$ were equal for the absorber, non-reciprocal, and gain sections. The lifetime of a photon was τ_c =3.73 ps, the isolation ratio α was 10 dB, the loss induced by metallic layer γ was 150 $\mathrm{cm^{-1}}$ and injection rate of carrier density into non-reciprocal section was $Q_2=1.3\times10^{27}\,\mathrm{cm^{-3}s^{-1}}$, which corresponds to injection current of 20.8 mA for active region volume of 100 μm^3.

For reversed direction of magnetization of the ferromagnetic layer, the direction of isolation is also reversed. Then, for the magnetization of ferromagnetic layer, which corresponds to the isolation direction from absorption to gain sections, instead of (3) we used:

$$I_1(x=a)=\alpha\cdot I_3(x=b)$$

III. Results

Figure 2 shows static characteristics of the photon density in gain section as a function of current injection rate Q_1 into this section. Three cases of bistable LD's are shown: LD without ferromagnetic layer (r_1=r_3=0.5, r_2=0), LD with ferromagnetic layer magnetized so that isolation directed from gain to absorption section (r_1=r_3=0.45, r_2=0.1), and LD with isolation directed from absorption to gain section (r_1=r_3=0.45, r_2=0.1). Bistability loop of LD with ferromagnetic layer magnetized so that the isolation directed from gain section to absorber section is significantly enlarged comparing with the loop of LD

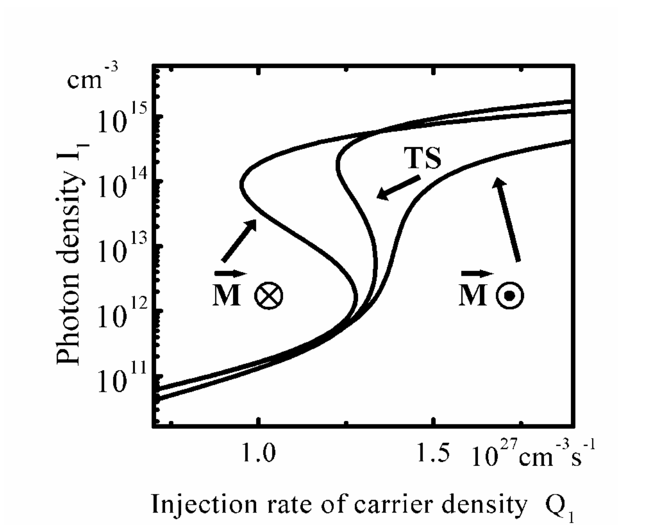

Fig.2 The static characteristic of the photon density in gain section as a function of current injection rate Q_1 into this section. Three cases of bistable laser are shown: two-sectional LD without ferromagnetic layer (TS), LD with ferromagnetic layer magnetized so that isolation is directed from gain to absorption sections ($\vec{M}\otimes$), and LD with ferromagnetic layer magnetized so that isolation is directed from absorption to gain sections ($\vec{M}\odot$).

without ferromagnetic layer. For LD with isolation directed from absorption to gain section, there is no bistability loop. Figure 3 shows the photon density distribution along the laser cavity for LD without and with non-reciprocal section. Photon density distributions along sections were calculated using gain coefficients obtained from (5). For LD without non-reciprocal section, the photon density distribution along the cavity is almost homogeneous. For LD with non-reciprocal section, it is strongly inhomogeneous. In the case of isolation directed from gain to absorber section, the average photon density in absorber section is significantly larger than in gain section (Fig.3b). Therefore, for the given photon density in gain section the saturation of absorber section of this LD with ferromagnetic layer (Fig.3b) is much stronger than the saturation of absorber section of LD without ferromagnetic layer (Fig.3a). Since saturation of absorber section is responsible for appearance of bistability loop, the bistability loop is significantly enlarged in the case of LD with ferromagnetic layer magnetized so that the isolation directed from gain to absorber section. In contrary, when isolation directed from absorber to gain section, the average intensity in absorber section is much smaller than in gain section (Fig.3c). Thus, the output characteristics of this LD are more similar to the output characteristics of one-section

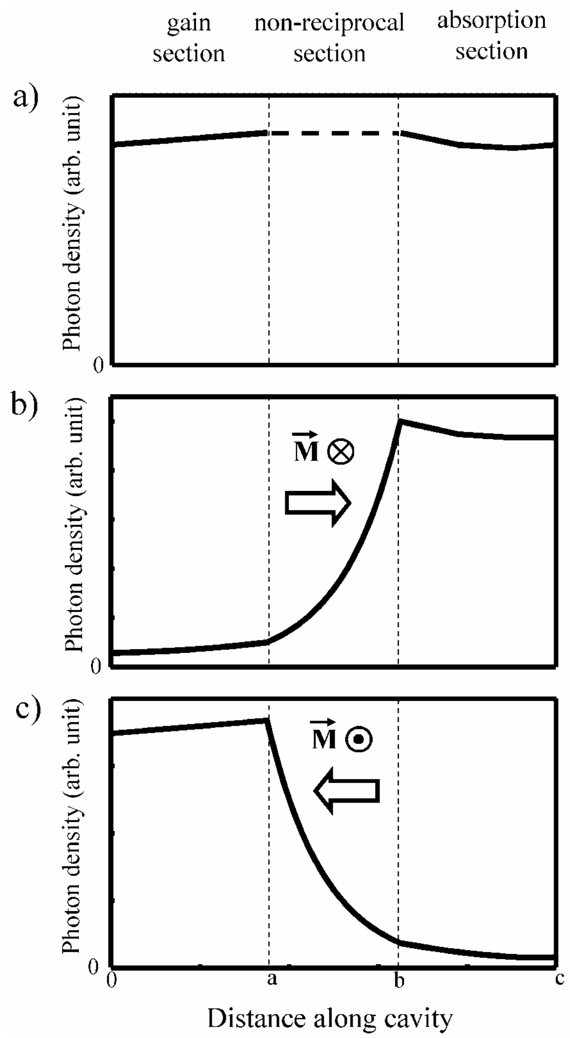

Fig.3 Photon density distribution along the cavity. a) Two-sectional LD without ferromagnetic layer (r_1=r_3=0.5, r_2=0). b) Three-sectional LD with ferromagnetic layer magnetized so that isolation is directed from gain to absorption sections layer (r_1=r_3=0.35, r_2=0.3). c) Three-sectional LD with ferromagnetic magnetized so that isolation is directed from absorption to gain sections (r_1=r_3=0.35, r_2=0.3). The arrow shows a direction of isolation. Injection rate of carrier density into gain section is $Q_1 = 1.45\times10^{27}\,\mathrm{cm}^{-3}\mathrm{s}^{-1}$.

LD and there is no bistability loop.

Figure 2 shows that the output characteristics of LD with non-reciprocal section are significantly different for two opposite direction of magnetization of ferromagnetic layer. There is large bistability loop for one direction and there is no bistability loop for another direction. Therefore, the bistability of LD with non-reciprocal section can be programmed by external magnetic field using a hysteresis effect of the ferromagnetic films.

Width of bistability loop is determined only by magneto-optical coefficients of a ferromagnetic metal and a structure design. For turning the bistability loop on or off the strength of external magnetic field is required only to be large than coercive field of ferromagnetic metal. For Co film it is about 200-300 Oe. For soft ferromagnetic materials it can be as small as 10 Oe. The magnetization reversing time can be shorter than a nanosecond.

It should be noticed that ability to modify photon flux distribution inside a cavity is a unique feature of non-reciprocal effect. It can be used in cavity-based non-linear devices in which high intensity of light is required on one side of a cavity and low intensity on another side. Also, since magnetization of ferromagnetic materials sustains when the electricity is off, the use of a ferromagnetic material extends functionality of bistable laser diodes to become re-programmable. For example, the proposed magnetically programmable bistable laser diode can be a good candidate as a switching element for re-programmable optical logical circuits.

IV. Conclusion

We studied a three-sectional bistable laser diode with non-reciprocal section inserted between gain and absorption sections. The non-reciprocal section is made of the semiconductor optical amplifier covered by ferromagnetic layer. The width of hysteresis loop of this bistable laser diode is significantly enlarged comparing with bistability loop of laser diode without ferromagnetic layer. There is a large difference in output characteristics of the laser diode for opposite directions of the magnetization of the ferromagnetic layer. The bistability itself can be switched on or off by reversing magnetization of ferromagnetic layer.

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