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The Effect of Polarization Flipping Point on Polarization Dynamics by Optical Feedback Technique

Ehsan Ali Abed[1], Jassim Mohammed Najim[2], Suaded Salman Ahmed[2]
[1]Department of Physics, University of Anbar, Anbar, Iraq
[2]Department of Physics, University of Baghdad, Baghdad, Iraq

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Abstract
The effect of the optical feedback on the polarization flipping point and hysteresis loop was studied. The polarization flipping occurred at all angles between the polarizer axis and the laser polarization. The polarization flipping point changed by an optical feedback occurred at angles from 0° to 90°. Ability of choosing or controlling the laser polarization was determined by changing the direction of vertical and horizontal polarization by polarizer rotation in the external cavity from 0° to 90°.

Keywords: Laser; Optical feedback; Polarization flipping point; hysteresis loop

تأثير نقطة تقلب الاستقطاب على ديناميكية الاستقطاب بواسطة تقنية التغذية العكسية البصرية

احسان علي عبيد[1]، جاسم محمد نجم[2]، سوؤدد سلمان احمد[2]
[1]قسم الفيزياء، جامعة الانبار، الانبار، العراق
[2]قسم الفيزياء، جامعة بغداد، بغداد، العراق

الخلاصة
تأثير التغذية العكسية البصرية على نقطة تقلب الاستقطاب وحلقة التأخير تمت دراسته. تقلب الاستقطاب حدث عند كل الزوايا بين محور المستقطب واستقطاب الليزر. تغير نقطة تقلب الاستقطاب بواسطة التغذية العكسية البصرية يحدث عند الزوايا من 0^o الى 90^o . امكانية اختيار او السيطرة على استقطاب الليزر حدد بواسطة تغيير الاتجاه للاستقطاب العمودي والافقي بواسطة تدوير المستقطب في التجويف الخارجي من 0^O الى 90^O .

1. Introduction

Polarization is a very fundamental property of light that is necessary to consider for the vertical characteristics of electromagnetic waves. Many approaches in optics are decided through the polarization states of the considered beams. Recently, studies on the polarization of light in lasers with optical feedback have attracted remarkable attention [1-4]. Floch *et al.* observed polarization switches and a hysteresis effect via changing the intracavity anisotropy values of the laser [1, 5]. Stephan *et* al. experimentally and theoretically studied the polarization adjustments brought about by means of optical feedback from a polarizer that is external to the cavity [6].

With the aid of the reflecting part of the laser output back into the resonant cavity, the conduct of the laser, in particular the static and dynamic residences, can be appreciably affected. This is called the optical feedback effect, or self-mixing interference, which was first suggested by king and Steward

*Email: abedehsan202@gmail.com

[7]. Theoretically, and to verify experimentally the polarization switching techniques happening in a gas laser when an internal parameter along with the laser frequency as an example turned into various [8].

This paper includes the following steps:

1. The polarization flipping point leads to the production of the hysteresis loop (HL) between the horizontal (//) and vertical (⊥) polarization for the He-Ne laser. The HL leads to a decrease in the two components of intensity ($I_{//}$ and $I_{\perp}$).
2. This problem is treated by optical feedback from the external cavity or reflector (M_3).
3. In previous investigations, researchers took few angles for optical feedback by polarizer rotation in the external cavity for the treatment of this problem.
4. In our paper, we took multiple angles for optical feedback by polarizer rotation in the external cavity. Therefore, the two components intensity values ($I_{//}$ and $I_{\perp}$) became high and the HL size became small. The results in our research are remarkably different from those in previous studies.

2. Experimental setup

Figure-1 shows the layout of experimental setup. The setup consists of three elements, namely the feedback, laser, and detection elements.

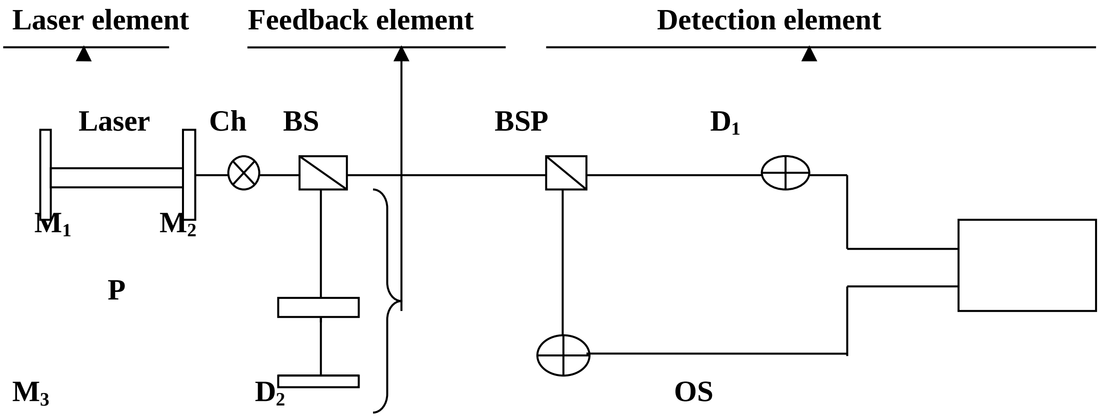

Figure 1-The Layout of experimental setup and unique coordinates. M_1, M_2 cavity mirrors; Ch, chopper; BS, beam splitter; P, rotating polarizer; M_3, feedback mirror; PBS, polarizing beam splitter ; D_1, D_2, photo detectors; OS, digital storage oscilloscope.

The intra-cavity He-Ne laser generates a linear polarization with a single longitudinal mode oscillating in the resonant cavity. The working wavelength is 632.8 nm. The gaseous pressure ratios in the laser tube are He: Ne = 9:1 and Ne20: Ne22 = 1: 1. The reflectivity values of the cavity mirrors M_1 and M_2 are 99.99% and 99%, respectively. The length of the resonant cavity formed by the mirrors M1 and M2 is 40 cm [9].

The feedback element is made of a chopper Ch., a feedback mirror M_3, and a polarizer P. The feedback cavity length is about 60 cm. The reflectivity of M_3 is 99.99%. The angle between the X axis and the optical axis of the polarizer is denoted by θ. The light whose polarization is parallel to the X axis is denoted by //-polarization, and the other one is denoted by ⊥-polarization.

The detection element consists of a polarizing beam splitter PBS, photo detectors D_1, D_2, and a digital storage oscilloscope OS. The ⊥-polarization and //-polarization are separated by the PBS, and their intensities ($I_{\perp}$ and $I_{//}$) are detected by D_1, D_2, and OS, respectively.

3. Theoretical analysis

A theoretical version based totally on self-consistency of the laser became available. Helium-neon (He-Ne) laser oscillates in two orthogonally polarized modes in the resonant cavity. The two modes transmit through M_2 and are reflected by the beam splitter to the polarizer. Firstly, the //-mode transmits through the polarizer to the feedback mirror M_3 and then it reflects by M_3 into the resonant cavity again. From the intra cavity, the electric vector $E_{//1}(t)$, and from the external cavity, the electric vector $E_{//2}(t)$, combine together into the intra cavity to obtain $E_{//}(t)$ and, hence, the feedback effect is generated [9].

$$E_{//}(t) = E_{//1}(t) + E_{//2}(t) \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

$$E_{//1(t)} = r_1 r_2\, exp\left(i4\pi v_{//}\, L/c + 2g_{//}L\right)E_{//o}(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

$$E_{//2(t)} = T_{ch} r_{bs} T_p r_2 r_3 T_2^2 M_{//} exp\left[i4\pi v_{//}\,(L+l)/c + 2g_{//}L\right] E_{//o}(t) \ldots\ldots\ldots\ldots\ldots..(3)$$

According to the self-consistency of the laser, the following equation is produced

$$E_{//}(t) = E_{//o}(t) \ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

$$\mathrm{E}_{//}(\mathrm{t}) = \mathrm{r}_1\mathrm{r}_2\,\exp\left(\mathrm{i}4\pi\nu_{//}\,\mathrm{L/c} + 2g_{//}\mathrm{L}\right)\mathrm{E}_{//\mathrm{o}}(\mathrm{t}) + \mathrm{T}_{\mathrm{ch}}\mathrm{r}_{\mathrm{bs}}\mathrm{T}_{\mathrm{p}}\,\mathrm{r}_1\mathrm{r}_3\mathrm{t}_2^2 M_{//}\exp\left[\mathrm{i}4\pi\,\nu_{//}\,(\mathrm{L}+\mathrm{l})/\mathrm{c} + 2g_{//}\mathrm{L}\right]\mathrm{E}_{//\mathrm{o}}(\mathrm{t}) \ldots\ldots\ldots(5)$$

where r_1, r_2, r_3 and r_{bs} are the reflection coefficient of M_1, M_2, M_3, and the beam splitter, respectively, t_2 is the transmission coefficient of M_2, and T_p and T_{ch} are the transmissivity values of the polarizer and chopper, respectively. $M_{//}$ is the factor brought about through Jones matrix for polarizers [7]

$$\mathrm{M}_{//} = \cos^4\theta + \sin^2 2\theta/4 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

$\nu_{\|}$ is the frequency of horizontal polarization (//-polarization). L and l are the laser cavity and the feedback cavity lengths, respectively. g is the linear gain per unit length due to the simulated emission inside the resonant cavity with the availability of the external feedback.
Equations (4) and (5) can be solved to obtain [10–12]

$$\Delta g = -\beta M cos\left(4\pi\frac{\nu l}{c}\right) \qquad \ldots\ldots\ldots(7)$$

$$\Delta g_{//} = -\Delta g_{\perp} = -\beta M cos\left(4\pi\frac{\nu l}{c}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots..(8)$$

$$\Delta g_{//} = -\beta M_{//} cos\left(4\pi v_{//} l/c\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots.(9)$$

where $\beta = \mathrm{T_{ch} r_{bs} T_p r_3 t_2^2 / r_2}$

$\Delta g_{//} = g_{//} - g_{//o}$

where $g_{//}$ and $g_{//o}$ represent the gain with and without feedback, respectively. When vertical polarization (⊥-polarization) oscillates, the following equation can be obtained

$$\Delta g_{\perp} = \beta M_{\perp} cos(4\pi v_{\perp} l/c) \qquad \ldots\ldots\ldots\ldots..(10)$$

$\Delta g_{\perp} = g_{\perp} - g_{\perp o}$

where $g_{\perp}$ and $g_{\perp o}$ represent the gain with and without feedback, respectively.
$M_{\perp}$ is the factor brought about through Jones matrix for polarizers

$$M_{\perp} = sin^4\theta + sin^2 2\theta/4 \qquad \ldots.\ldots..(11)$$

As illustrated in Eqs. (9) and (10), $\Delta g_{//}$ and $\Delta g_{\perp}$ are both modulated by θ (from the rotating polarizer) and feedback cavity length l. Furthermore, there is a phase difference between $\Delta g_{//}$ and $\Delta g_{\perp}$ due to the frequency difference between $v_{//}$ and $v_{\perp}$. By supposing that $v_{//}$ is larger than $v_{\perp}$, $\Delta g_{//} - \Delta g_{\perp}$ is denoted as G_{Δ} which may be expressed as in eq . (12)

$$G_{\Delta} = \beta\left[M_{//} cos\left(\alpha + \frac{2\pi\Delta v l}{c}\right) - M_{\perp} cos\alpha\right] \qquad \ldots\ldots\ldots\ldots.(12)$$

where $\alpha = 4\pi v_{\perp} l/c$ **.** G_{Δ} is modulated by l, θ and Δν . The amplitude of G_{Δ} is denoted as G , which is modulated by θ and Δν**.**

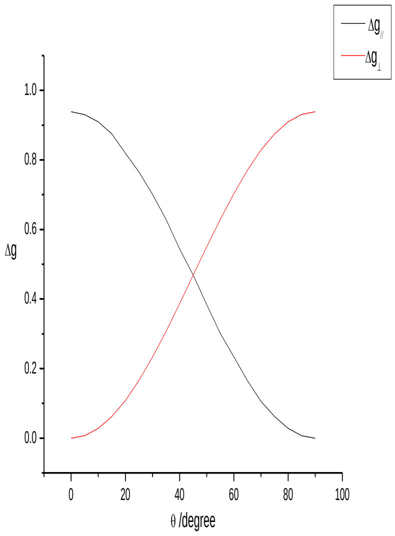

Fig.2. Δg changes along with θ.(throretically)

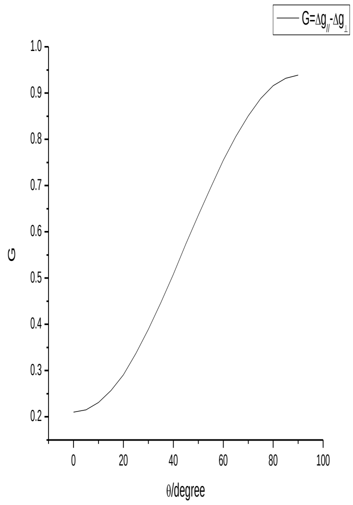

Fig.3 G changes along with θ. (theoretically)

Figure 2-indicates that Δg changes with θ from the rotating polarizer. $\Delta g_{//}$ for horizontal polarization increases at θ=0 then decreases at θ=90. $\Delta g_{\perp}$ for vertical polarization decreases at θ=0 then increases at θ=90. The polarization flipping occurs at θ=45. Figure-3 indicates that G changes along with θ. Also, G increases with the increase of θ. There is no polarization flipping at any angle.

The laser intensity with optical feedback can be expressed as [13]

$$I = I_o\,(1 - k\Delta g) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(13)$$

where k is a constant relating to the laser operation parameters and I_o is the initial laser intensity without optical feedback.

By substituting Eq. (9) and Eq.(10) into Eq.(13), the intensities of the two modes with optical feedback can be written as

$$I_{//} = I_{//o}\left[1 + k_{//}\,\beta M_{//} cos\left(\frac{4\pi\nu_{//} l}{c}\right)\right] \qquad \ldots\ldots\ldots\ldots\ldots(14)$$

$$I_{\perp} = I_{\perp o}\left[1 - k_{\perp}\,\beta M_{\perp} cos\left(\frac{4\pi\nu_{\perp} l}{c}\right)\right] \qquad \ldots\ldots\ldots\ldots\ldots..(15)$$

where $I_{//o}$ and $I_{\perp o}$ are the intensities of the two polarized modes without optical feedback. $I_{//}$ and $I_{\perp}$ are the intensities of the two polarized modes with optical feedback.

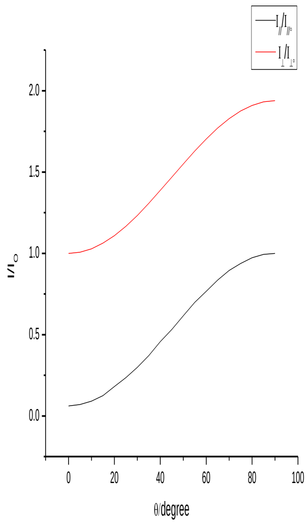

Fig.4 I/I, changes along with θ.(throretically)

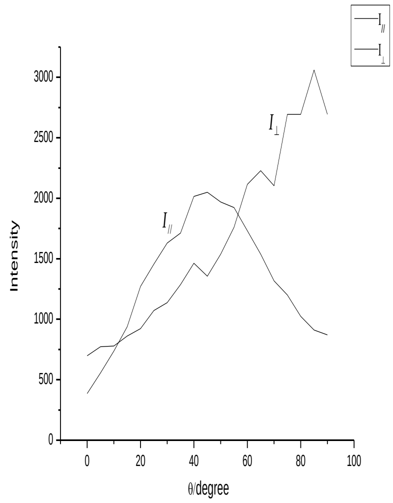

Fig. 5.Intensity changes along with θ(experimentally)

Figure 4-shows that $\frac{I_{\perp}}{I_{\perp o}} \geq \frac{I_{//}}{I_{//o}}$ with the optical feedback. This theoretical result is identical to the practical result in Figure- 5, where $I_{\perp}$ with the optical feedback is much greater than the $I_{//}$ with the optical feedback at 90°. Also, there is no polarization flipping between $I_{//}/I_{//o}$ and $I_{\perp}/I_{\perp o}$ (theoretically).

Figure-5 shows that polarization flipping occurs between $I_{//}$ and $I_{\perp}$ at $\theta = 10^{o}$ and $\theta = 60^{o}$ with optical feedback. Also, $I_{\perp} \geq I_{//}$ at $\theta = 90^{o}$ with optical feedback (experimentally).

4. Results and discussion

Figures- 6 to 14 show that the polarization flipping from x-to-y is obtained without and with optical feedback**.** Figure-6 shows horizontal(//) and vertical(⊥) polarization without optical feedback. One can observe that $I_{//}$ and $I_{\perp}$ intensity are stable and that the polarization flipping point does not move because of the absence of the optical feedback. Figure-7 shows that //- polarization oscillates and $I_{//}$ is modulated by optical feedback because of the combination between $\mathbf{E_{//1}(t)}$ and $\mathbf{E_{//2}(t)}$ into the intra cavity. While ⊥-polarization does not oscillate, $I_{\perp}$ is stable because of the presence of the polarizer. In this case, the polarization flipping point moves to the right. When the polarization flipping point moves to the right, $I_{//}$ increases and the hysteresis loop decreases.

In Figures- 8 to 11, it is shown that $I_{//}$ increases and the hysteresis loop decreases, while $I_{//}$ reaches to saturation state. Figures- 12, 13, and 14 show that ⊥-polarization oscillates and $I_{\perp}$ increases because of the combination between $\mathbf{E_{\perp 1}(t)}$ and $\mathbf{E_{\perp 2}(t)}$ into the intra cavity. Figures- 15 to 25 show that the polarization flipping from y-to-x is obtained. Figure-15 shows that the polarization flipping point moves to the left, $I_{\perp}$ increases, and the hysteresis loop decreases. Figures-16 to 25 show that $I_{\perp}$ increases and the hysteresis loop decreases, while $I_{\perp}$ reaches to the saturation state.

$I_{\perp}$ is higher than $I_{//}$ and the hysteresis loop does not disappear at //- polarization oscillation, while it disappears at ⊥-polarization oscillation.

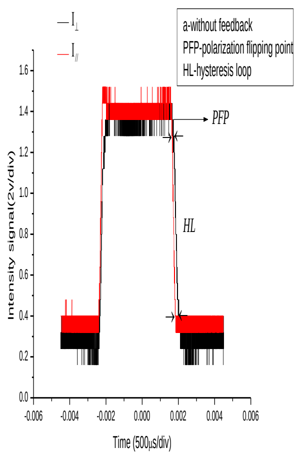

Figure 6-The intensities of $I_{//}$ and $I_{\perp}$ without optical optical feedback

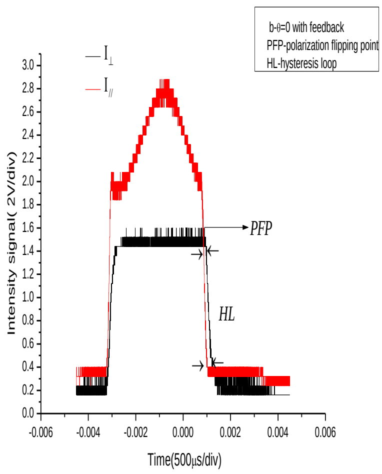

Figure 7- The intensities of $I_{//}$ and $I_{\perp}$ with feedback at θ=0°

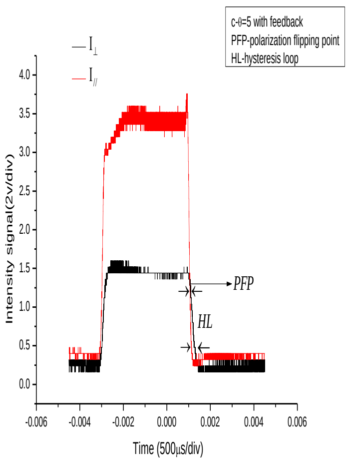

Figure 8-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=5°

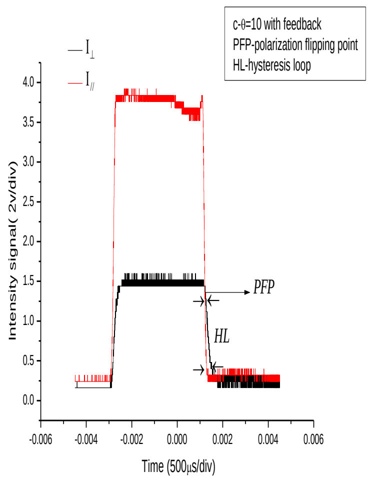

Figure 9-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=10°

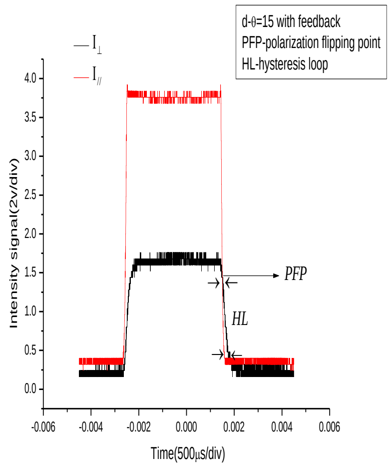

Figure 10 -The intensities of $I_{//}$ and $I_{\perp}$ with feedback at θ=15^{o}

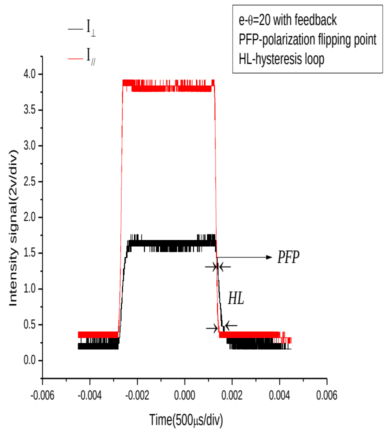

Figure 11-The intensities of $I_{//}$ optical and $I_{\perp}$ with optical feedback at θ=20^{o}

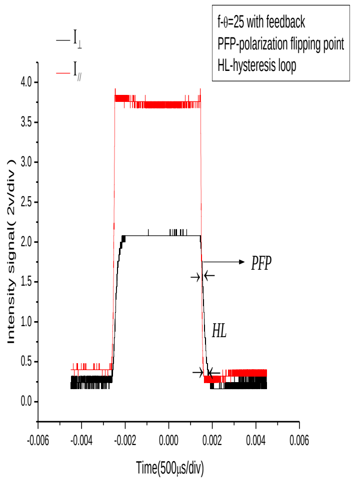

Figure 12-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=25^{o}

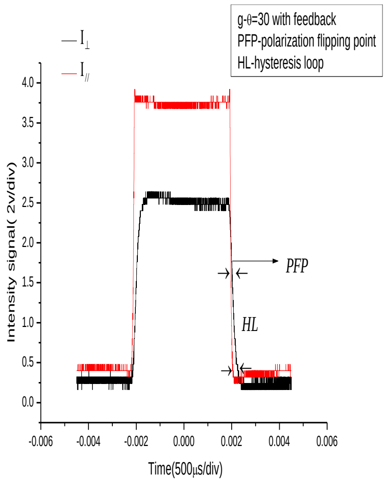

Figure 13-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=30^{o}

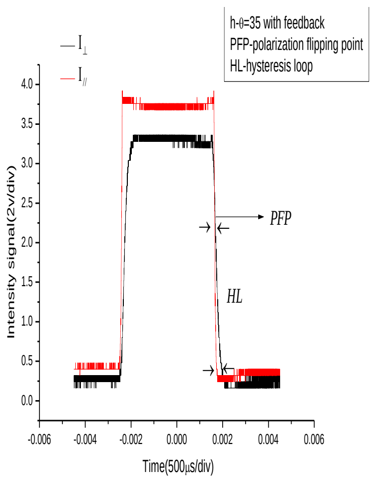

Figure 14 -The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=35^{o}

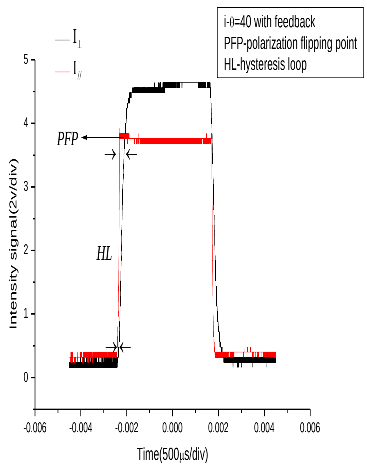

Figure 15- The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=40^{o}

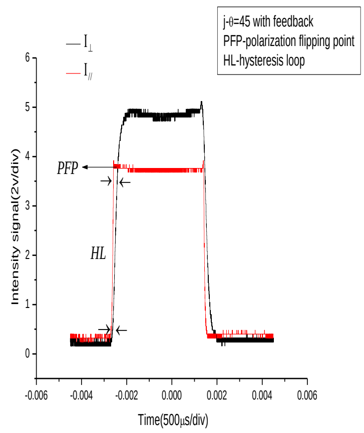

Figure 16 -The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=45°

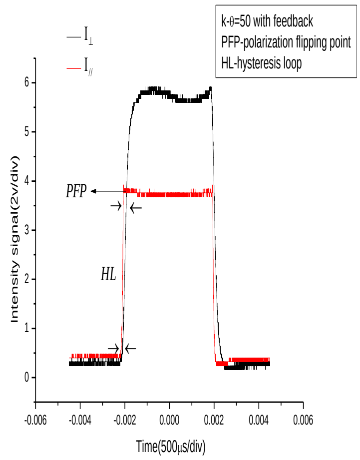

Figure 17- The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=50°

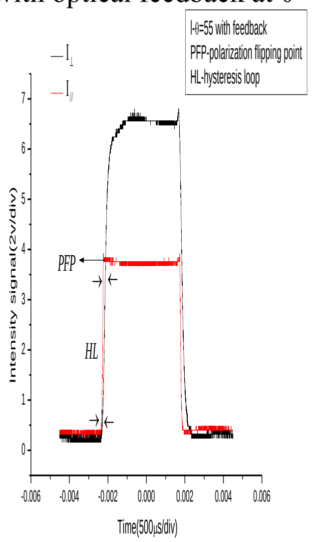

Figure 18-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=55°

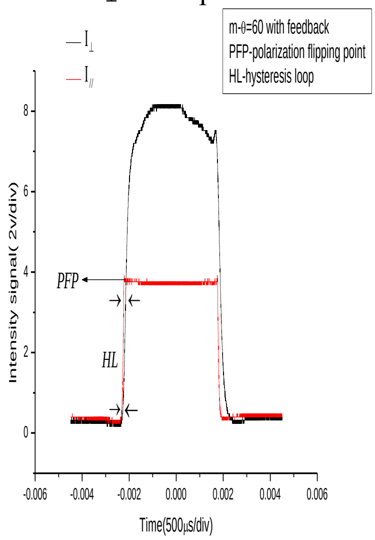

Figure 19- The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=60°

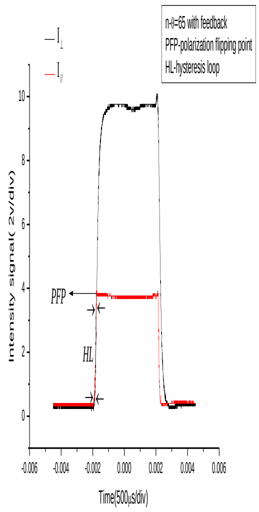

Figure 20-The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=65°

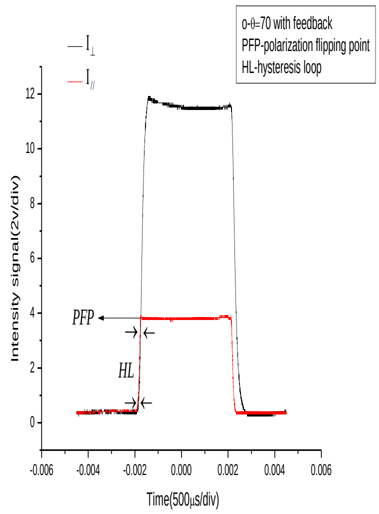

Figure 21 -The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=70°

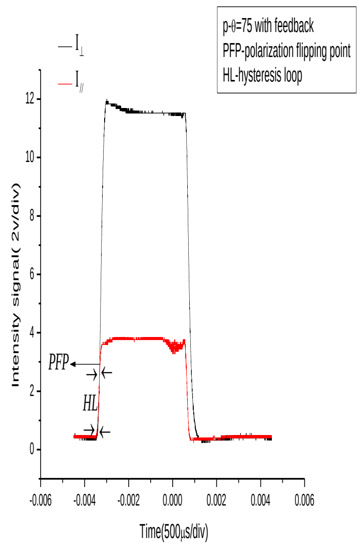

Figure 22- The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=75°

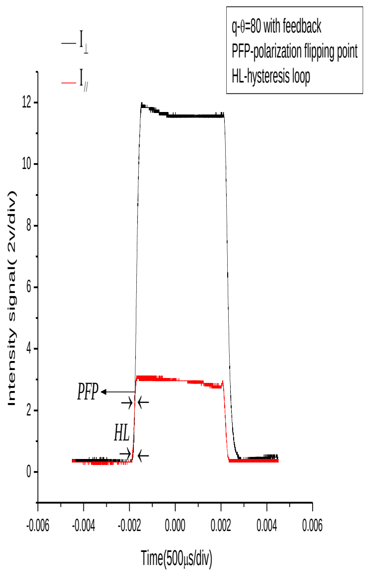

Figure 23- The intensities of $I_{//}$ and $I_{\perp}$ with optical feedback at θ=80°

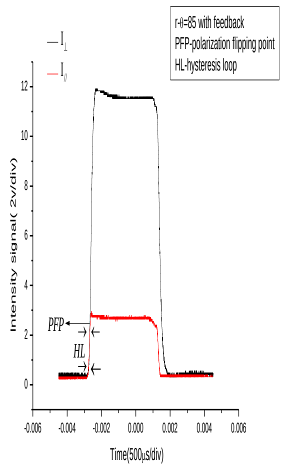

Figure 24-The intensities of $I_{//}$ and $I_{\perp}$ with feedback at θ=85°

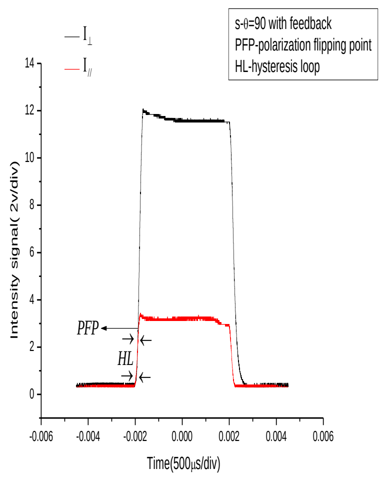

Figure 25 -The intensities of $I_{//}$ and $I_{\perp}$ with optical optical feedback at θ=90°

5. Conclusions

We have proved that the polarization flipping point moves once to the right and another to the left by optical feedback. The intensity of the two components ($I_{//}$ and $I_{\perp}$) can be adjusted by polarizer rotation in the external laser cavity. The control on the vertical and horizontal polarizations is achieved by the polarizer in the external laser cavity. This is also a simple design that does not need a change in the structure of the laser or the adoption of complex optical elements. The control on the hysteresis loop between the vertical and horizontal polarizations can be performed by an optical feedback technique from the external cavity.

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