Iraqi Journal of Physics, 2020 *Vol.18, No.45, PP. 32-39*

DOI: 10.20723/ijp.18.45.32-39

Optimum diameter for laser beam and effect of temperature rise on the optical bistability hysteresis loops

Ali H. Khidhir

Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

E-mail: alzurfialiali@gmail.com

Abstract

In this research, analytical study for simulating a Fabry-Perot bistable etalon (F-P cavity) filled with a dispersive optimized nonlinear optical material (Kerr type) such as semiconductors Indium Antimonide (InSb). An optimization procedure using reflective (~85%) InSb etalon (~50µm) thick is described. For this etalon with a (50 µm) spot diameter beam, the minimum switching power is (~0.078 mW) and switching time is (~150 ns), leading to a switching energy of (~11.77 pJ) for this device. Also, the main role played by the temperature to change the etalon characteristic from nonlinear to linear dynamics.

Key words

Etalon optimization, switching dynamics.

Article info.

Received: Feb. 2020
Accepted: Apr. 2020
Published: Jun. 2020

القطر الأمثل لحزمة الليزر وتأثير ارتفاع درجة الحرارة على الأستقرارية الثنائية البصرية لحلقات الهسترة

علي حسن خضر

قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

في هذا العمل ، تم اجراء دراسة تحليلية لمحاكاة مرنان فابري-بيروت (تجويف F-P)، والمملوء بمادة شبه موصلة لاخطية عالية التشتت (نوع كير) مثل انديوم-أنتيمونايد (InSb). حيث تم إجراء دراسة تحليلية لإيجاد الحالات المثلى لهذا المرنان لسمك (50µm) وانعكاسية (85%). وجد أنّه باستخدام ليزر ذي حزمة قطرها (50µm)، سيكون أقل طاقة للفتح البصري هي (0.078 mW) وزمن الفتح (150ns)، وينتج عن ذلك طاقة فتح بصري حوالي (11.775 pJ). كذلك لتغير درجة الحرارة تاثير كبير على تغير سلوك المادة وتحولها من الديناميكية اللاخطية الى السلوك الخطي.

Introduction

Since the appearance of the photonic crystal concept, there has been a strong interest in the optical properties of nano- and microstructured systems. This is due, in part, to the potential applications for small all-optical devices. An interesting possibility is to include some nonlinear elements in the structures, which may result in optical switches and gates. Systems based on nonlinear photonic crystals presenting optical bistability have been recently proposed [1]. Optical bistability - the existence of two stable states with different photon numbers for the same driving conditions - is a general feature of driven nonlinear systems described within the mean-field approximation (MFA) [1, 2]. Beyond the MFA, a quantum treatment predicts that the steady-state of a nonlinear cavity is unique at any driving condition. The origin of this apparent contradiction was noted by Alexander et al. [3].

Quantum fluctuations (the lost feature in the MFA) trigger switching between states and the exact solution corresponds to a weighted average over the two metastable states.

Optical Fabry-Perot cavities are common in laser spectroscopy and interferometry and are frequently used for the stabilization of laser sources [1, 2]. A novel application for high-finesse cavities was proposed in the early 90's in the upcoming field of cavity-QED: Single atoms are strongly coupled to a cavity-stored photon field such that the mutual coherent oscillatory exchange between both sub-systems is much faster than their individual decay rates.

Dispersive optical nonlinearities enable all-optical functionalities including optical memories optical switches [4, 5], and optical signal processors [6, 7]. Renewed interest in these devices is driven by their potential to reduce system complexity and latency, for example in chip-level optical interconnects [8].

Optical bistability can be achieved in several ways, including via thermo-optic effects [9], carrier injection [10], a combination of both [7, 8], or via optoelectronic feedback [7, 10]. Unfortunately, all these methods are inherently slow, as they implicitly or explicitly rely on carrier generation. Another way to achieve optical bistability is via nonlinear optical effects.

Several parameters should be considered in order to get a fully optimized device such as the beam spot size, the etalon thickness, the frequency of the input beam, and the absorption coefficient. Many attempts have been made to get the optimum conditions of low switching power and fast switching speed of the bistable devices using different specifications such as high finesse case [10] and low finesse case [11, 12].

In this work, the results obtain to conduct analytical study for simulating a Fabry-Perot bistable etalon filled with a nonlinear optical material (Kerr type) such as semiconductors Indium Antimonide (InSb) illuminated with a pulse laser. The theoretical study of a fully optimized InSb etalon (high finesse etalon) is studied in order to obtain a faster switching time with a minimum power. From this work, the effect of the temperature rise on the hystersis loop is cleared, a MATHLAB program used to study the optical bistability, switching dynamics and optimization of a nonlinear Fabry-Perot Etalon.

Theoretical work of optical nonlinearities on InSb etalon

From the studies of Frank [12], the critical switching irradiance can be estimated using:

$$I_c = \left[\frac{\lambda\alpha}{3\pi n_2}\right] f\left(R_f\ , R_b\ , \alpha D\right) \qquad (1)$$

where λ is the beam wavelength, α is the absorption coefficient, n_2 is the nonlinear refractive index while R_f, R_b and αD which appear in the cavity characteristics factor represent the front face, back face reflectivity of the etalon and the absorption length respectively.

The ambipolar diffusion length (L_D) is a measure of how far a carrier population diffuses before recombination and is defined by $L_D = \left(D_a \tau_R\right)^{\frac{1}{2}}$, where τ_R is the recombination time and D_a is the ambipolar diffusivity and proportional to the ambipolar mobility. The semiconductor InSb in which optical bistability and other band gap resonant nonlinear effects have been extensively studied, has a measured diffusion length of ~60μm. This value being much longer than easily achievable focused spot sizes makes InSb an ideal material for the study of transverse diffusive effects in optical bistability [12].

It has been speculated [13] that when the focusing beam radius on the bistable element is less than the diffusion length, the carriers will diffuse out and fill the same volume.

The relation between the switching power and spot diameter is given by [13]:

$$P_c = \frac{\pi L_D^2}{2} g\left(\frac{\omega_o}{L_D}\right)\frac{\hbar c}{\sigma_n \tau} f\left(R_f, R_b, e^{-\alpha D}\right) \quad (2)$$

where

$$g(x) = \frac{8e^{\frac{-x^2}{8}}}{Ei\left(\frac{x^2}{8}\right)} \quad , \quad x = \frac{\omega_o}{L_D} \quad (3)$$

ω_o is the spot diameter, and:

$$Ei(x) = \int_x^\infty \frac{e^{-u}}{u}\, du \quad (4)$$

when $R_f R_b = e^{-4\alpha D}$, the cavity factor takes a minimum value and for a high finesse may be written as [14]:

$$f\left(R_f, R_b, \alpha D\right) = \frac{8}{3\sqrt{3}} \frac{\left(1-\sqrt{R_f R_b}\, e^{-\alpha D}\right)^2}{\left(1-R_f\right)\left(1+R_b e^{-\alpha D}\right)\left(1-e^{-\alpha D}\right)} \frac{1}{\sqrt{F}} \quad (5)$$

And when $R_f = R_b$, the minimum cavity factor is:

$$f_{\min} = \frac{3\sqrt{3}}{2}\left(1-R_f\right) \quad (6)$$

Which is about 0.39 for $R_f = R_b = 0.85$. For high finesse case the cavity factor (when $R_f=R_b$) is as eq.5. The switching power becomes:

$$P_c = \frac{\pi L_D^2}{2} \frac{8e^{-\omega_o^2/8L_D^2}}{\ln\left(\frac{\omega_o^2}{8L_D^2}\right) - \left(\frac{\omega_o^2}{8L_D^2}\right) + \left(\frac{\omega_o^4}{256 L_D^4}\right) - \left(\frac{\omega_o^8}{4608 L_D^8}\right)} \cdot \frac{\hbar c}{\sigma_n \tau} f\left(R_f, R_b, e^{-\alpha D}\right) \quad (7)$$

The bandgap absorption edge of InSb which lies near (7 μm, Eg = 0.18 eV) wavelength at room temperature moves to shorter wavelength on cooling passing through (5.5 μm, Eg = 0.23 eV) at liquid nitrogen temperature (77 K). The heating effect of either the absorbed optical power or any externally applied heat input can result in a number of significant changes to the parameters relevant to a near band gap probe beam. The principal consequence of a temperature rise (ΔT) is a decrease in the InSb energy bandgap $d\upsilon/dT=-2cm^{-1}K^{-1}$ which gives rise to the following three changes [15]:

(i) An increase in absorption (α_0) to a value given approximately by:

$$\alpha_o = \exp\left(\frac{\Delta T}{17.1}\right) \quad (8)$$

Assuming $\Delta T \leq 10$ k, and the operating wavenumber (υ) to be within the range ($1802\ cm^{-1} \leq \nu \leq 1840\ cm^{-1}$).

(ii) An increase in the linear refractive index (n_o) which we have measured as $dn_0/dT=1.2\text{x}10^{-3}K^{-1}$ in this wavelength region.

(iii) An increase in the magnitude of (σ), Δn/ΔT, given by:

$d|\sigma|/dT = 2.6\ \text{x}10^{-20}\ cm^3K^{-1}$.

Assuming equivalence between a thermal shift of the band gap and a change in operating wavelength.

All these effects have been taken into account when successfully modeling the response of a bistable InSb etalon to pulsed incoherent illumination [15]. In addition, the absorption change has been exploited in demonstrating induced absorption bistability [16].

Finally, the dependence of (n_o) upon temperature has permitted a demonstration of thermal refractive bistability in InSb at temperature using (10.6μm) wavelength radiation.

In a thin material where D <<ω_o the temperature rise can be estimated as follows [8, 17]:

$$\Delta T = \Delta T_o \frac{2}{\pi}\tan\left(\frac{t_p}{t_o}\right) \tag{9}$$

where D is the sample thickness, ω_o is the beam spot size, t_p is the switching time, and ΔT_0 is the steady state temperature rise within the spot, is given by:

$$\Delta T_o = \frac{\Delta P}{2k\,\omega_o\,\sqrt{\pi}} \tag{10}$$

where $t_0 = \omega_0^2/4D_a$ is the thermal diffusion time, D_a is the diffusivity constant, and k is the thermal conductivity.

$$\Delta P = \frac{\left(1-R_f\right)\left(1-R_b\,e^{-\alpha L}\right)\left(1-e^{-\alpha L}\right)}{\left(1-R\right)^2}\left(\frac{F}{1+F}\right)P_{in} \tag{11}$$

where ΔP is the difference of the input power (P_{in}) of the laser beam that is absorbed in the etalon from switch OFF to switch ON resonance condition.

Results and discussion

The power necessary to switch the device ON (switch up) is plotted in Fig.1 as a function of spot diameter for a high finesse etalon 50μm thick (85% reflectivity of both faces). This is in agreement with the experimental work of Hagan et al. [16].

It can be seen from this graph that the minimum switching power is ~0.0785 mW as compared with 0.785 mW for a low finesse etalon.

However, for a low and high finesses of etalon the surface recombination becomes important factor as the beam spot size increases due to more carriers reaching the surface, but this importance of surface recombination is diminished by reduction in the spot size and thereby the switching power decreases. Therefore, the above results support the point that with a high finesse etalon the switching power will decrease due to the improvement in the optical feedback and the enhanced nonlinear phase change. Our results are agree with the results of Khidhir [17-19].

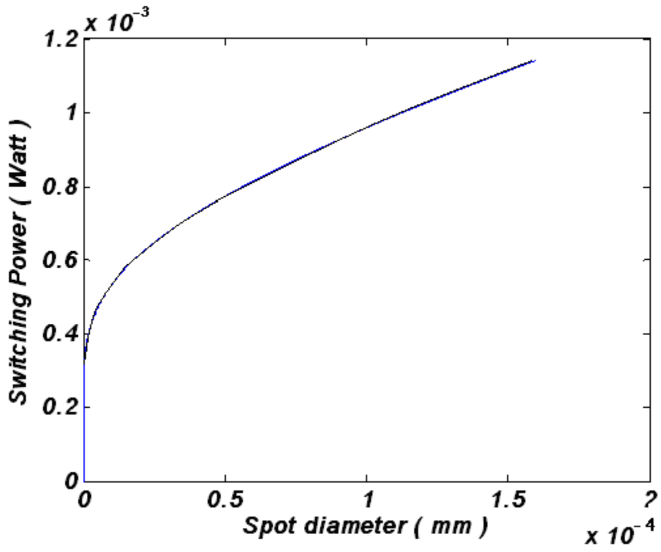

Fig.1: Switching power versus spot diameter calculated from eq.7 for a high finesse.

Now, suppose that an InSb etalon was fixed on a 2mm thick molybdenum disk. For spot size (ω_0) larger than (k_1/k_2)D, where k_1 and k_2 are the InSb, molybdenum thermal conductivity respectively.

We can assume that a constant temperature prevails across the etalon and the thermal diffusion takes place through the molybdenum disk only. Using etalon parameters of natural reflectivity on both faces $(R_f = R_b = 0.36)$, laser source of λ=5 µm, ω_o=125 µm, D=110 µm, $k_1=k_2$=1.79, $D_{a\ mol}$=1.35, t_o=29 µsec, and P_{in}=10 mW. The temperature rise using eq.9 is $\Delta T=2\times10^{-2}$ K for this device. These results are closed to with research of Rodriguez et al. and Leyong Jiang et al. [4, 15]. Also, the corresponding round-trip phase shift can be obtained using:

$$\Delta\varphi = \frac{2\omega_o D}{c}\frac{dn}{dT}\Delta T \qquad (12)$$

where

$$\frac{dn}{dT} = 1.2\times10^{-3}\ k^{-1}$$

$$\therefore \quad \Delta\varphi = 6\times10^{-3}$$

So, the temperature changes and the detuning (round-trip phase shift) changes, which mean the hystersis loop changes as well as shown in Fig.2.

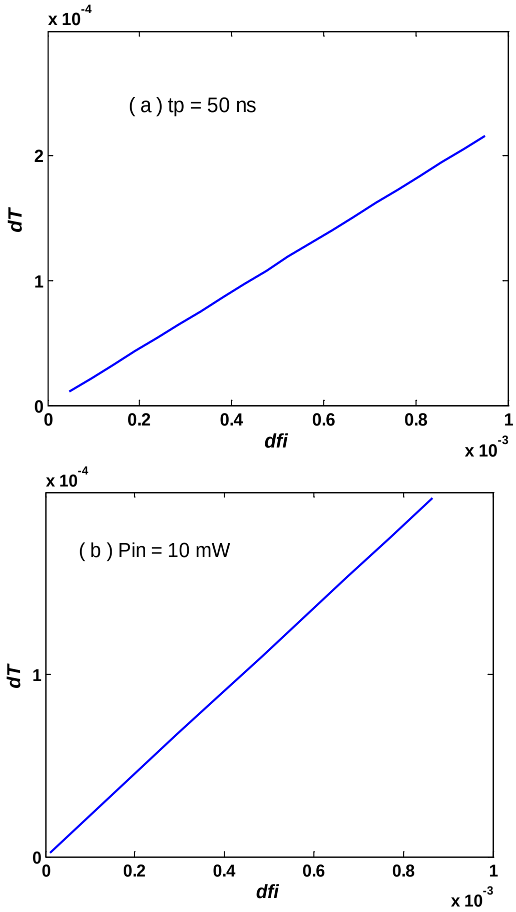

Fig.2: The detuning (round-trip phase shift) changes as a function of temperature change: (a) for constant switching time and (b) for constant incident power.

Also, as the temperature of the sample changes, the shape of hystersis loop will change too due to the change in detuning as shown in Fig.3 (a, b, c and d).

From different hystersis loops the switch ON and switch OFF power against the temperature were plotted in Fig. 4. From this figure the effect of the temperature rise on the hystersis loop is clear. So, over the temperature of 90 K no switching power or (no hystersis loop) will appear, just nonlinear characteristic and when the temperature becomes higher, the nonlinear characteristic disappear leaving a linear characteristic. For this etalon with a 50 µm spot diameter beam, the minimum switching power is ~0.078 mW and switching time is ~150 ns, leading to a switching energy (E_s) of ~11.77 pJ. These organization and results are close to the researcher's findings of Alexander et al. [3].

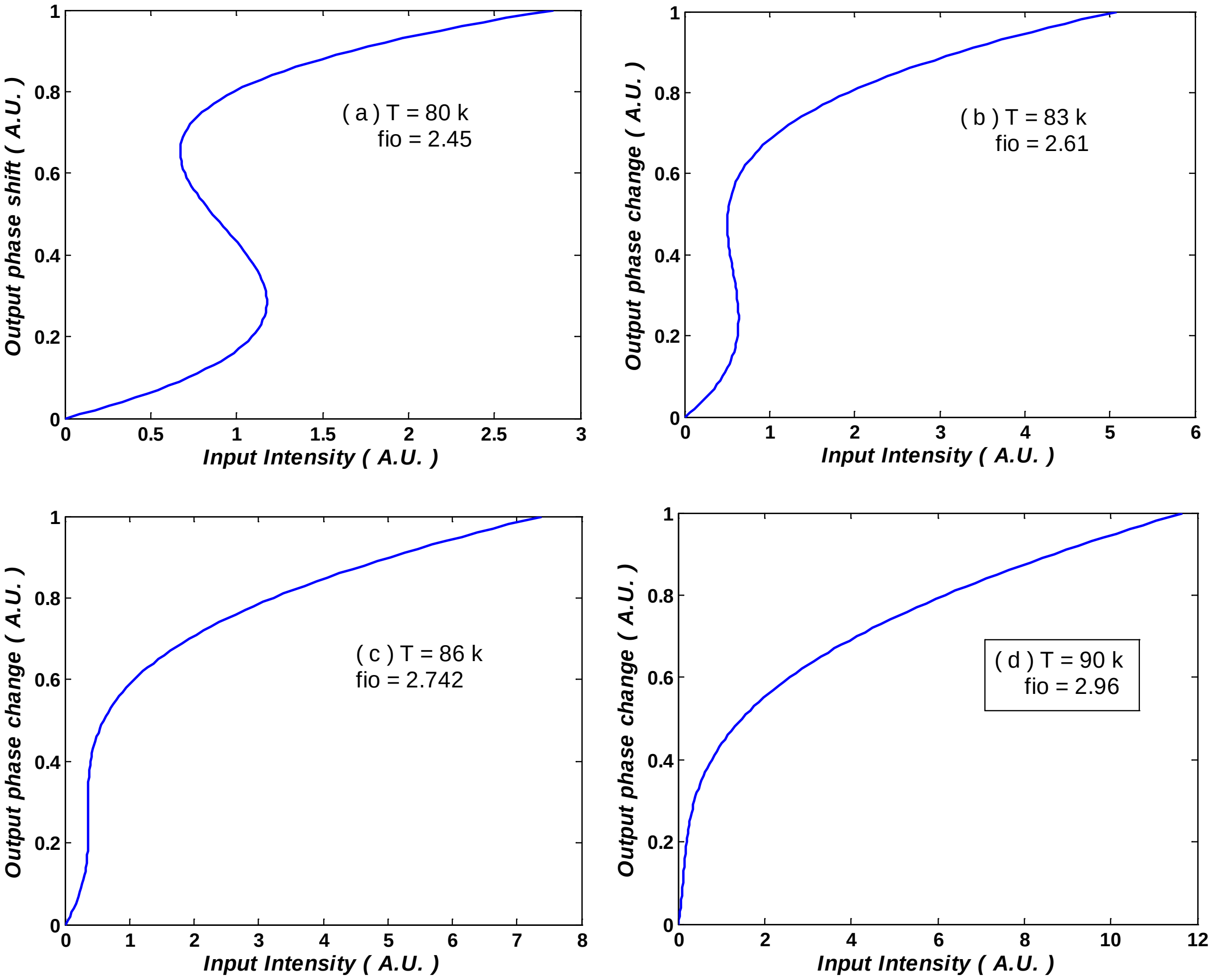

Fig.3: Input / output intensity characteristic for different etalon temperature: (a) large loop, (b) small loop, (c) critical switching, and (d) optical nonlinear nonlinearity characteristic respectively.

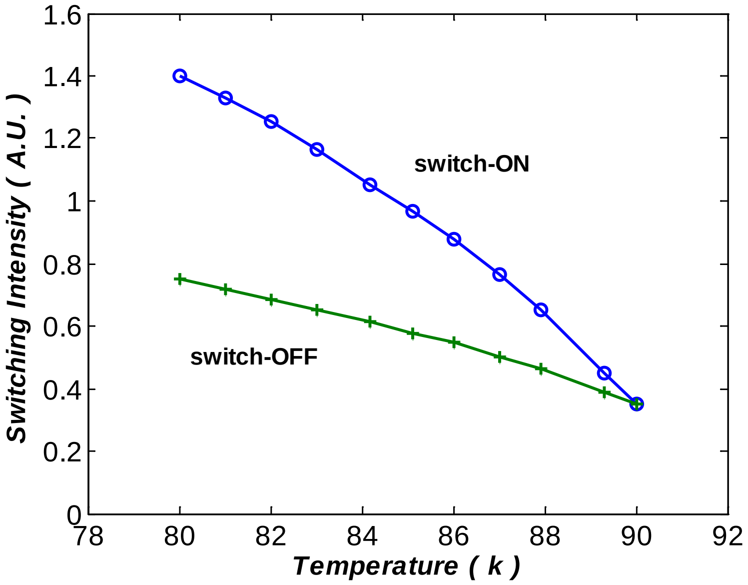

Fig.4: The temperature against the switch-ON & OFF intensity.

These results justified the main role played by the temperature to change the etalon characteristic from nonlinear to linear, i.e. the nonlinear characteristic and the bistability hystersis loop of the InSb will appear when the sample is cooled with a liquid nitrogen to a temperature of 80 K or more than that using a CW CO laser (λ=5.5 μm) to illuminate the sample.

Conclusions

In this research, good results were obtained using Fabry-Perot device for the laser beam, which reached 50μm and the lowest conversion capacity reached 0.078 mW, and a small conversion power of 11.77 pJ. The results also showed that over the temperature of 90 K, there will be no switching force and there are no optical hystersis loops. When the temperature rises above these levels, the non-linear feature will disappear and remain linear only for this resonance. This result is close to the results of other researchers, especially working under comparable conditions [3, 16, 18].

References

[1] J. A. Porto, L. Martín-Moreno, F. J. García-Vidal, Phys. Rev., B 70 (2004) 081402-1_ 081402-4.

[2] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hansch, J. Reiche, Fiber Fabry-Perot cavity with high finesse, Opt. Lett., 1 (2010) 1-24.

[3] P. Alexander, C. Aurelian, B. Arnaud, S. Genrikh, V. Andrey, Materials and Nanotec., 11 (2015) 9-12.

[4] S.R.K. Rodriguez, W. Casteels, F. Storme, N. Carlon Zambon, I. Sagnes, L. Le Gratiet, E. Galopin, A. Lemaitre, A. Amo, C. Ciuti, J. Bloch, Opt. Lett., 9 (2017) 1-9.

[5] Joanna A. Zielińska and Morgan W. Mitchell, Opt. Lett., 42, 24 (2018) 5298-5301

[6] M. Rakhmanov, R.L. Savage, Jr., D.H. Reitze, D.B. Tanner, Phys. Lett., A 305 (2002) 239-244.

[7] Thomas Corbitt, David Ottaway, Edith Innerhofer, Jason Pelc, and Nergis Mavalvala, Physical Review, A 74 (2006) 021802-1_ 021802-4.

[8] I.N. Agishev, N.A. Ivanova, A.L. Tolstik, Opt. Commun., 19, 6 (2002) 199-209.

[9] J. V. Moloney, M. R. Belic, H. M. Gibbs, Optical Communications, 41, 5 (1982) 379 - 382.

[10] D. Kim and J.I. Choi, Progress in Electromagnetic Research Letters, 7 (2009) 59-68.

[11] L. R. Brovelli and V. Keller, J. Opt. Soc. Am. B, 12, 2 (1995) 311-322.

[12] D. Frank, Optical Comm., 62, 1 (1987) 61-66.

[13] Thijs Klaassen, Martin P. Van Exter, J.P. Woerdman, Applied Optics, 46, 22 (2007) 5210-5215.

[14] P. Wierzba and Jedrzejewska-Szczerska, ACTA Physica Polonica A, 124, 3 (2013) 586-588.

[15] Leyong Jiang, Jun Guo, Leiming Wu, Xiaoya Dai, Yuanjiang Xiang, Optical Express, 23, 24 (2015) 31181-31191.

[16] D. J. Hagan, H. A. MacKenzie, J. J. E. Reid, A.C. Walker, F.A.P. Tooley, Appl. Phys. Lett., 47, 3 (1985) 203-205.

[17] Ali H. Khidhir, Iraqi Journal of Physics, 16, 39 (2018) 152-161.

[18] Ali H. Khidhir, Iraqi Journal of Science, Special issue, (2019) 129-134.

[19] Ali H. Khidhir, Iraqi Journal of Science, 59, 4B (2018) 2012-2019.