

Explanation of the Effect of Magnetic Field on laser Intensity on the Basis of Generalized Special Relativity

Ahmed Zakaria¹, M. Dirar Abd- Allah¹, Rasha Abd ALhi¹, Kh. M. Haroun^{2,3}, Ahmed EL Hassan ELfaki¹, R. Abd Elgani¹, Hilo, M. H. M¹

¹Department of Physics, Faculty of Science, Sudan University of Science and Technology, Khartoum11113, Sudan

²Department of Physics, Faculty of Education, Al-Azhari University, Khartoum Bahri –Sudan

²Department of Physics,

³Department of Physics, College of Arts and Science in ALmikhwah, ALbaha University, ALmikhwah- Saudi Arabia

Abstract: *Laser technology recently becomes one of the widespread technologies in many applications. This attracts attention to generation of laser and the mechanisms affecting this generation. One of the recent developments in lasing is the so-called free-electron laser (FEL) which is based on special relativity (SR). FEL shows that lasing intensity is affected by a magnetic field. However, the theoretical framework of this effect is complex and cannot explain the effect of the magnetic field on lasers produced by materials. These setbacks motivate to search for a new model based on generalized special relativity to account for these theoretical defects. In this work, the generalized special relativity accounts for the effect of magnetic fields on laser intensity produced by matter theoretically. These theoretical relations agree with the empirical ones for plasma, discharge gas and semiconductor lasers.*

Keywords: Free electron laser, Magnetic field. Potential, Laser intensity, Generalized, special relativity, amplification factor

1. Introduction

Laser technology is one of the biggest achievements of theoretical physics [1, 2]. It comes directly from the discovery and prediction of the so called stimulation emission which was proposed by Einstein [3]. This phenomenon shows the possibility of light amplification by stimulated emission of radiation to produce laser [4]. Laser can be produced by different mechanisms [5]. It can be produced by population inversion [6], or by non inversion process by polarized atoms or by free electrons in a magnetic field [7, 8, 9]. The effect of magnetic field on free electrons shows the possibility of observing the same effect on matter. This was really observed experimentally as shown in section (2). This effect is explained theoretically in section (3). Sections (4) and (5) are devoted for discussion and conclusion.

2. The Effect of Magnetic field on Laser Intensity

The first demonstration of large soft-x-ray amplification in a discharge-driven plasma was recently realized using a fast capillary discharge to generate a hot and dense plasma column in which collisional electron excitation of Ne-like Ar ions produced amplification in the $J = 0 - 1$ line of Ne-like Ar at 46.9 nm. In this excitation scheme, a fast current pulse rapidly compresses the plasma, creating a hot and narrow plasma column with length-to-diameter ratios approaching 1000:1. During the final stage of the compression, plasma conditions for soft-x-ray amplification by collisional excitation are obtained. In the initial experiments, a gain-

length product of $g_l \sim 7.2$ at 46.9 nm was reported for a 12-cm - long plasma column.

The experiments were conducted in a capillary discharge excited, collisionally pumped 46.9-nm Ne-like Ar amplifier [7]. In the experiments the generator was used to excite plasmas in polyacetal capillaries 4 mm in diameter and 10 cm in length with current pulses having a first half cycle duration of approximately 64 ns. The axial magnetic field was generated by a 9-cm diameter, 15-cm long coil positioned concentrically with the capillary channel. The coil, which was excited by a current pulse with a period of 200 μ s is obtained by discharging a 420- μ F capacitor through a spark gap, was used to produce magnetic fields up to 0.3 T. The intensity of the magnetic field was selected by varying either the capacitor charging voltage or the delay time between the triggering of the latter spark gap and the firing of the fast capillary discharge. The soft-x-ray radiation exited the capillary through the hollowed ground electrode. The laser radiation was collected by a cylindrical copper mirror of 13 cm in radius and focused onto the slit of a 2.2-m vacuum spectrometer provided with a 1200 l/mm diffraction grating placed at 4.2° with respect to the incoming radiation. The detection system consisted of an intensified charge-coupled device (CCD) array detector that was gated by pulsing the gain on the multichannel plate intensifier with a high voltage pulse with duration of about 25 ns. The variation of the measured integrated intensity of the Ar IX 46.9-nm laser line as a function of the magnetic field strength is shown in Fig (1) [7]. The laser intensity increases with the magnetic field and reaches a maximum at approximately 0.15 T decreasing monotonically for higher field strengths. The same figure also shows the calculated variation of the intensity corresponding to two calculations

which differ from each other in the inclusion of Zeeman splitting of the laser line. In both computations the laser intensity first increases to subsequently decrease at higher values of the magnetic field. The intensity increase is due to decreased refraction losses and to a larger electron temperature caused by a decrease in heat losses.

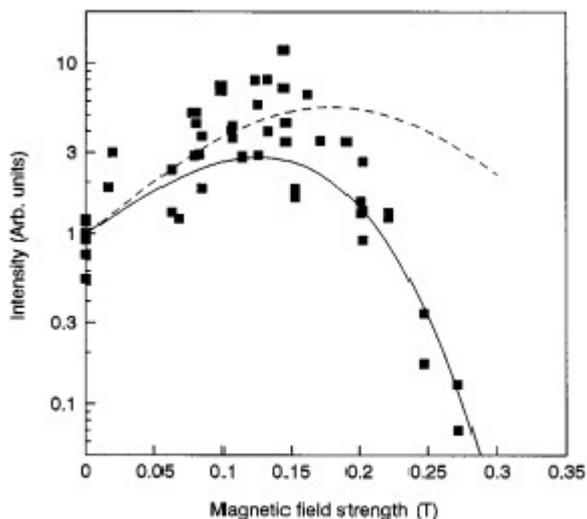


Figure 1: Variation of the integrated intensity of the 46.9-nm Ar IX laser line as a function of the strength of the externally applied axial magnetic field

These results suggest that the Zeeman effect is likely to be a major cause for the observed decrease of the laser output intensity at higher magnetic fields. The laser intensity decrease observed at large magnetic fields in the computation that excludes the Zeeman effect is the result of a smaller gain caused by a decrease in the density, reduced transient effects associated with ionization and excitation, and an increase in the optical depth. The larger optical depth

at higher magnetic fields is due to a reduction of the very important radial motional Doppler effect, which is in turn caused by the previously discussed reduction of the density gradients.

In another work weak axial magnetic field also affect He-Cd laser. In this work an internal cavity He-Cd laser which was 2.81 cm internal diameter and 72 cm in discharge lengths was used as is shown in fig (2). So that the polarization effects mentioned above could be observed [8]. The optical resonator, which was 136 cm in length, was composed of a mirror with a curvature radius of 3m and a reflectivity of 99% and an output coupling plane mirror with reflectivity of 98%. Mounted on a non-magnetic support, the laser tube was placed in a coaxial glass tube of larger diameter so that electrical leakage from the discharge capillary could be prevented to ensure the accuracy of measurement. A coil was wound around the coaxial glass tube (8.5 C/cm) and was supplied by an adjustable D.C. power set so that the strength of the WAMF could be changed.

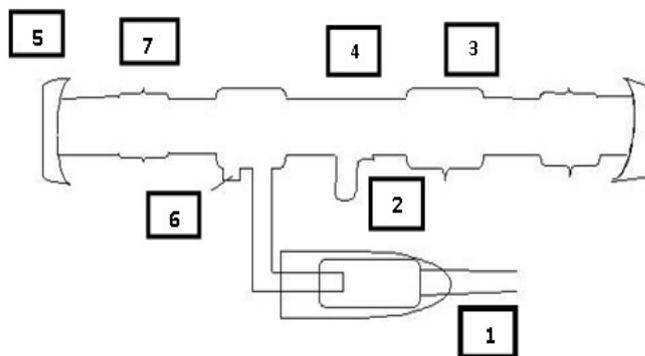


Figure 2: Structure of laser tube, 1- cathode, 2- Cd oven, 3- anode, 4- active bore 5- mirror, 6- auxiliary anode, 7- bellows

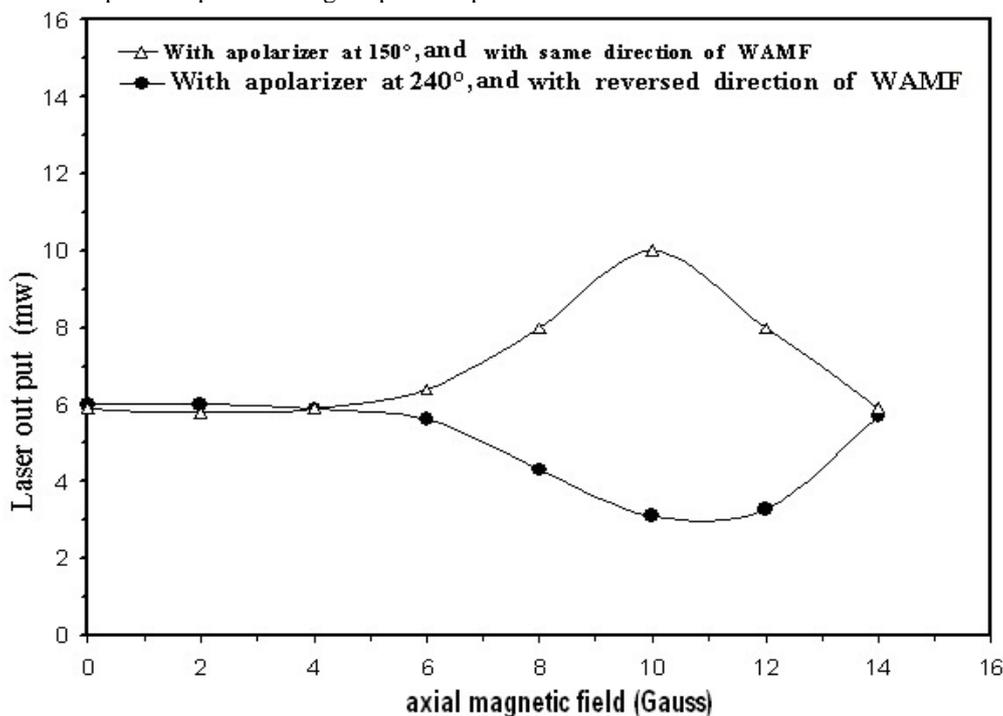


Figure 3: Laser output as a function of the WAMF strength, (Δ) with a polarizer at 150° with Same direction of WAMF, and (\bullet) with a polarizer at 240° with reversed direction of WAMF

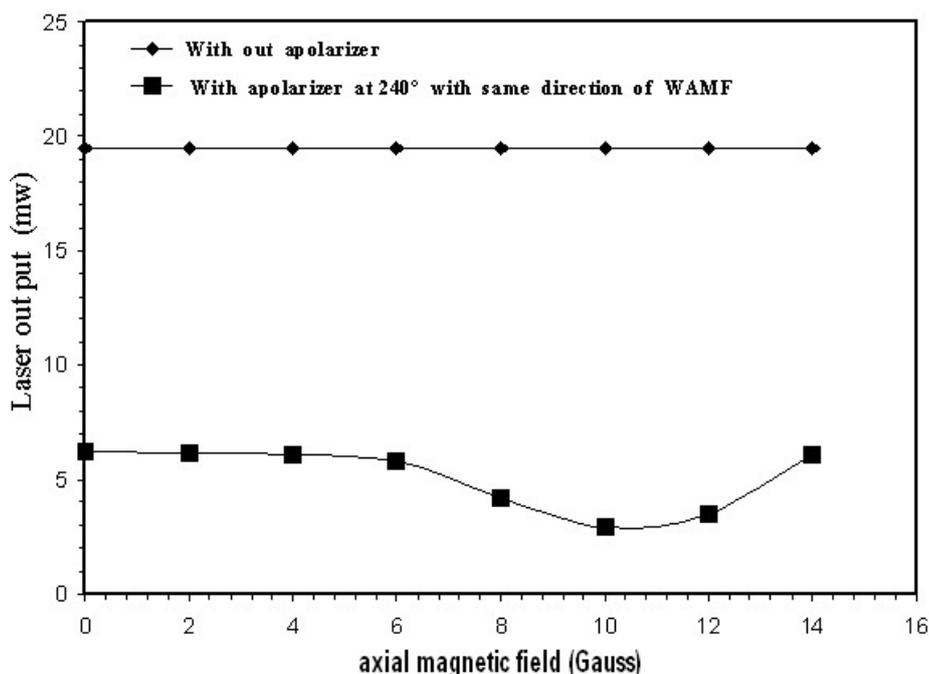


Figure 4: laser output as a function of the WAMF strength, (■) with a polarizer at 240° with Same direction of WAMF, (◆) without polarized laser output as a function of the WAMF strength with a polarizer at 150°, 240° with same direction of WAMF, and 240° with reversed direction of WAMF, and also without polarizer

The total output of the laser remained unchanged without the polarizer in front of the detector. It can be concluded that the weak axial magnetic field only changed the polarization of the laser rather than the gain of the laser. When a polarizer was inserted, however, the laser power varied with the weak axial magnetic field. The weak axial magnetic field causes the anisotropy of the laser gain, the rotation of the main polarization axis of the laser, and the change the laser output which is a function of the polarization direction of the polarizer. In figs. (3) and (4). the Lines marked with (Δ) and (■) refer to cases in which the polarization axis of the polarizer are at angles of 150° and 240° respectively with the abscissa, and there is difference of 90° between these two cases. The curves showing the laser output versus the weak axial magnetic field for these two cases in figs. 3 and 4 [8]. Vary in opposite direction. When the weak axial magnetic field was stronger than 10 Gauss, the laser output was modulated by more than 80% of its amplitude.

The work titled “Influence of magnetic field on laser “made by R. Abd Elgani (2003). Studied the effect of magnetic field on laser beam intensity and polarization. One has found that the magnetic field increases the polarization range and increases also the laser intensity by increasing the number of photons. The data as shown in table (1) [9], was obtained empirically and it relate the intensity of laser beam I (J/m²s) to the applied magnetic field H /T

Table 1: Relation of intensity of laser beam I (J/m²s) versus of the applied magnetic field H /T

H / T	I(J / m ² s)
0.039	8.972236×10 ⁻³
0.074	9.170857×10 ⁻³
0.100	9.300988×10 ⁻³
0.136	9.335233×10 ⁻³
0.167	9.348931×10 ⁻³
0.202	9.341119×10 ⁻³
0.231	9.513307×10 ⁻³
0.254	9.527005×10 ⁻³
0.282	9.568099×10 ⁻³
0.303	9.611560×10 ⁻³

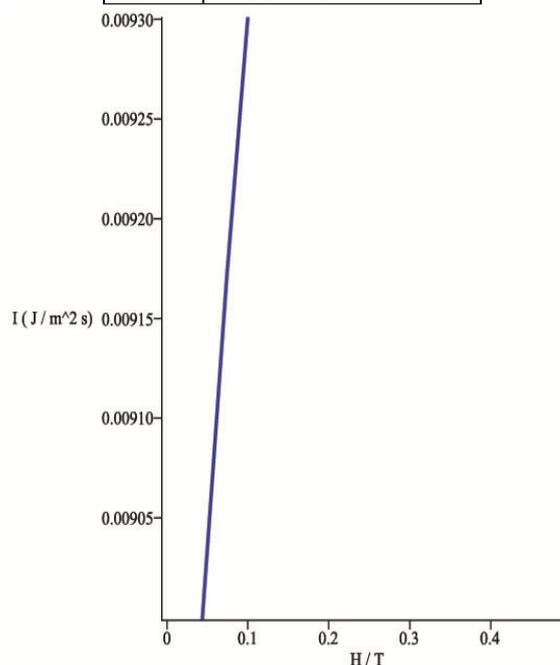


Figure 5: Intensity of laser beam I (J/m²s) versus of the applied magnetic field H /T

The intensity of laser beam as a function of the applied magnetic field is displayed in figure (5) according to table (1) [9]. Obtained that the laser intensity increases with increases of magnetic field [9]

3. The Effect of Magnetic field on Amplification factor and Intensity of Laser Beam according to Generalized Special Relativity

In Einstein general relativity (GR) the length, time, frequency and mass are not affected by fields. However in generalized special relativity (GSR), they are affected by any field. To see how can this happen, consider the amplification factor [10,11].

$$\beta = B(n_2 - n_1) \frac{hf}{c} \quad (1)$$

Where B is Einstein coefficient, n_2, n_1 are the number of atoms in the upper and lower level respectively.

If one takes into account the wave properties of light, the frequency f is related to the periodic time T according to the relation

$$f = \frac{1}{T} \quad (2)$$

But according to generalized special relativity GSR [12-14].

$$T = \gamma T_0 = T_0 \left(1 + \frac{2\phi}{c^2} - \frac{v^2}{c^2}\right)^{-1/2} \quad (3)$$

Where T_0 , is the time in the rest frame, ϕ is potential per unit mass, and v is the speed.

Thus,

$$f = \frac{\left(1 + \frac{2\phi}{c^2} - \frac{v^2}{c^2}\right)^{1/2}}{T_0}$$

Neglecting the velocity of frame of reference v , i.e. the atoms emitting photons, and for small ϕ .

$$f = \frac{\left(1 + \frac{2\phi}{c^2}\right)^{1/2}}{T_0} = \frac{\left(1 + \frac{2\phi}{c^2}\right)}{T_0} = \frac{\left(1 + \frac{m_0 \phi}{m_0 c^2}\right)}{T_0} = \frac{\left(1 + \frac{m_0 \phi}{m_0 c^2}\right)}{T_0} \quad (4)$$

But the magnetic flux density B induces a potential V given by

$$V = \frac{enB}{c} \quad (5)$$

Where n, is the number of particles per unit volume. Thus inserting equation (5) and (4) in (1) yields.

$$\beta = \frac{B_0(n_2 - n_1)}{cT_0} = \left(1 + \frac{eB}{m_0 c^2}\right)$$

This can be written as.

$$\beta = C_1[1 + C_2B] \quad (6)$$

With

$$C_1 = \frac{B_0(n_2 - n_1)}{cT_0}$$

$$C_2 = \frac{en}{m_0 c^3} \sim \frac{10^{-19}n}{10^{-31} \times 10^{25}} \sim 10^{-13} n$$

For $n \sim 10^{12}$ then $C_2 = 10^{-1}$ plotting equation (8) for I , where

$$I = I_0 e^{\beta L} \quad (7)$$

for small βL

$$I = I_0[1 + \beta L] = I_0[1 + C_1 + C_1 C_2 B] \quad (8)$$

The relation between I and B becomes as in figure (6).

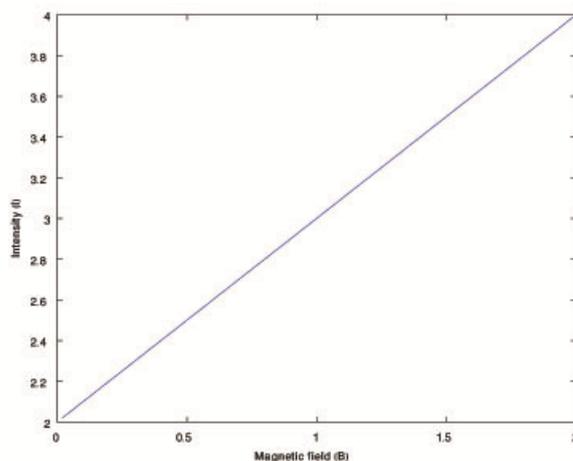


Figure 6: Relation between I and B

The relation between I and B can also be investigated, by considering the particle nature of light, where the mass is affected by the field according to equation (1), by replacing hf by mc^2 to get

$$\beta = B(n_2 - n_1)mc \quad (9)$$

And by using the relation [15].

$$m = \frac{g_{00} m_0}{\sqrt{g_{00} - \frac{v^2}{c^2}}} \quad (10)$$

m_0 stands for the rest mass, v is the speed and ϕ is the potential per unit mass [15-17], where

$$g_{00} = 1 + \frac{2\phi}{c^2}$$

$$\beta = B(n_2 - n_1) \frac{g_{00} m_0}{\sqrt{g_{00} - \frac{v^2}{c^2}}}$$

$$\beta = B(n_2 - n_1) \left(1 + \frac{2\phi}{c^2}\right) m_0 \left(1 + \frac{2\phi}{c^2} - \frac{v^2}{c^2}\right)^{-1/2} \quad (11)$$

Neglecting again v , for small ϕ , β , becomes

$$\beta = B(n_2 - n_1) m_0 \left(1 + \frac{2\phi}{c^2}\right) \left(1 - \frac{\phi}{c^2}\right) = C_3 \left(1 + \frac{\phi}{c^2} - \frac{2\phi}{c^2}\right) \quad (12)$$

Using equation (1)

$$\beta = C_3 \left(1 + \frac{enB}{m_0 c^3} - \frac{2e^2 n^2}{m_0^2 c^5} B^2\right) \quad (13)$$

$$\beta = C_3(1 + C_4B - C_5B^2)$$

Where,

$$C_3 = B(n_2 - n_1)m_0 \quad (14)$$

$$C_4 = \frac{en}{m_0c^3}$$

$$C_5 = \frac{2e^2n^2}{m_0^2c^5}$$

$$I = I_0 e^{C_3(1+C_4B-C_5B^2)} \quad (15)$$

Plotting I against B according to equation (15) one gets figure (7).

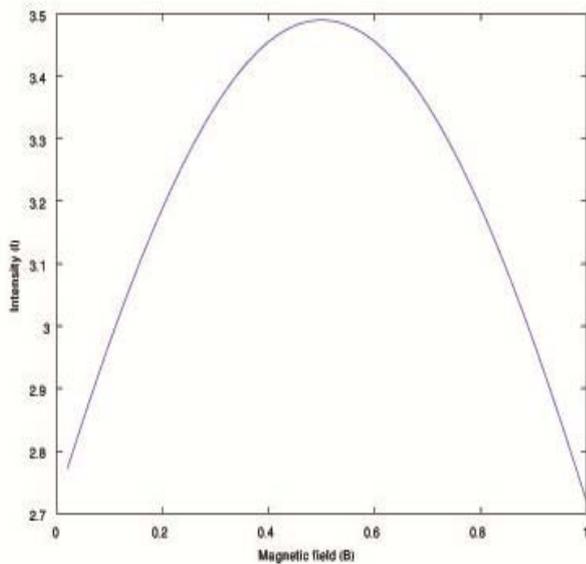


Figure 7: Relation between I and B

If one considers the electrons and atoms emitting laser photons, as harmonic oscillators, the situation becomes different. The amplification factor becomes according to equation in form [11].

$$\beta = \frac{2\pi^3 f}{3c} (n_2 - n_1)(n + 1)^2 m_0 \left(\frac{\omega}{m\omega^2}\right) \quad (16)$$

But according to harmonic oscillator model [11].

$$K = m\omega^2$$

Thus,

$$\begin{aligned} \beta &= \frac{2\pi^3 f}{3c} (n_2 - n_1)(n + 1)^2 m_0 \left(\frac{2\pi f}{K}\right) \quad (17) \\ &= \frac{4\pi^4 (n_2 - n_1)(n + 1)^2 f^2}{3c} \\ &= C_5 f^2 \end{aligned}$$

But,

$$f = \frac{1}{T} = \frac{\left(1 + \frac{2\theta}{c^2} - \frac{v^2}{c^2}\right)^{1/2}}{T}$$

Neglecting v and for small θ ,

$$f = \frac{\left(1 + \frac{\theta}{c^2}\right)}{T_0} = T_0^{-1} \left(1 + \frac{\theta}{c^2}\right)$$

Thus,

$$f = T^{-2} \left(1 + \frac{\theta}{c^2}\right)^2 = T_0^{-2} \left(1 + \frac{2\theta}{c^2} + \frac{\theta}{c^2}\right)$$

If the magnetic field opposes the motion

$$V = m_0 \theta = \frac{-enB}{c}$$

Therefore,

$$f^2 = T_0^{-2} \left(1 - \frac{2enB}{c} + \frac{e^2 n^2 B^2}{c^4}\right) \quad (18)$$

Inserting (18) in equation (17) yields

$$\beta = C_5 T_0^{-2} (1 - C_6 B + C_7 B^2)$$

$$\beta = C_8 - C_9 B + C_{10} B^2 \quad (19)$$

Thus,

$$I = I_0 e^{(C_8 - C_9 B + C_{10} B^2)} \quad (20)$$

Where, C_8 , C_9 , and C_{10} are constants that can be found by substituting the values of e , c and $n \sim 10^{12}$ plotting I versus B according to equation (20) yields figure (8).

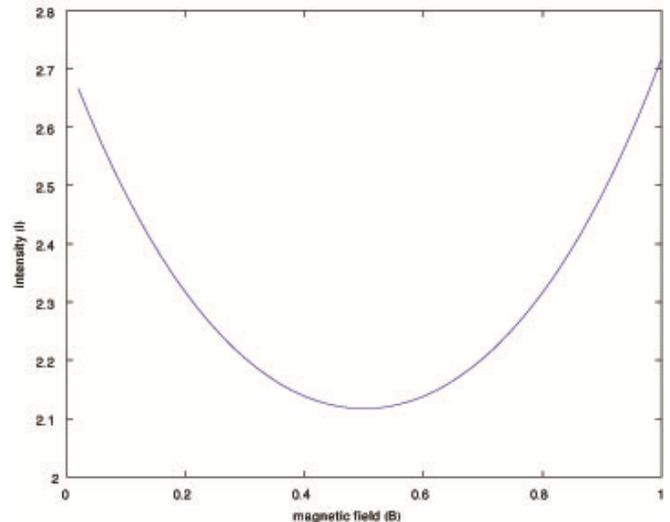


Figure 8: Relation between I and B

4. Discussion

The generalized special relativistic time and mass in equations (3), and (10) can explain the effect of magnetic field on laser amplification factor as well as laser intensity. The relations based on generalized special relativity, which relates laser amplification and magnetic field strength, can explain the empirical relations mentioned in section (2). Comparing the theoretical relation between I and B in figure (6), with the empirical relation in figure (5), it is clear that the two curves are similar. This is not surprising as well as the active lasing media is plasma which consist of free atoms that oscillates and act as a harmonic oscillator. The effect of magnetic field on Helium cadmium (He-Cd) laser discharged gas is displayed in figures (3) and (4) These empirical relations are similar to the theoretical relations in figures (7) and (8) which are concerned with particle nature of light and harmonic oscillator. This is not surprising since the discharged gas which has free isolated ionized atoms treat light as particles called photons with mass m . The ionized atoms also oscillate and thus behave as harmonic oscillator.

Finally the effect of magnetic field on semiconductor laser is linear as shown in figure (5). This empirical relation conforms to the linear theoretical one in figure (6), which

was derived by considering the change of frequency by the magnetic field. This is not surprising, since for the semiconductor laser, which is a bulk matter, light behaves as waves with a certain frequency.

5. Conclusion

The fact that generalized special relativity (GSR) predicts that the mass, time and length is affected by physical field open a new horizon for explaining a wide variety of physical phenomena on bases of GSR. The (GSR) succeeded in explaining the change of laser intensity with the magnetic field strength.

6. Acknowledgements

I would like to thank and send special greeting to Sudan University for Science and Technology (SUST), Umm Al qura University – Qunfudah University College and my friends for supports.

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Author Profile



Ahmed Zakaria Abubakar, received B.sc, High Diploma, and M.sc, in Sudan University for Science and Technology. Teaching Assistant – Physics in Umm AL-Qura University-AL-Qunfudah University College, AL-Qunfudah -Kingdom of Saudi Arabia – period of duty 2001 – 2009, and Lecturer – Physics, during the period of 2009 - 2014. Current position, Ph.D. Student in Sudan University for Science and Technology, Khartoum – Sudan.