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# NONPARAXIAL COEFFICIENTS INFLUENCE OF HIGH INTENSE LASER BEAM ON THE RELATIVISTIC SELF-FOCUSING INSIDE PLASM

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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FATIMAH DHARI JABBAR AL-KHRAYFAWEE

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By Fatimah Dhari Jabbar AL-KHRAYFAWEE

June 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

**Advisor** : Prof. Dr. Çiğdem YÜKSEKTEPE ATAOL
**Co-Advisor** : Prof. Dr. Munther Baqir HASSAN ALKHAQANI

**Examining Committee Members:**

**Chairman** : Prof. Dr. Çiğdem YÜKSEKTEPE ATAOL
Physics
Çankırı Karatekin University

**Member** : Prof. Dr. Sebahaddin ALPTEKİN
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Çankırı Karatekin University

**Member** : Assoc. Prof. Dr. Ayşin ZÜLFİKAROĞLU
Chemistry
Amasya University

**Approved for the Graduate School of Natural and Applied Sciences**

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**Fatimah Dhari Jabbar AL-KHRAYFAWEE**

# ABSTRACT


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Fatimah Dhari Jabbar AL-KHRAYFAWEE
Master of Science in Physics
Advisor: Assoc. Prof. Dr. Çiğdem YÜKSEKTEPE ATAOL
Co-Advisor: Prof. Dr. Munther Baqir HASSAN ALKHAQANI
June 2023

In this thesis, the self-focusing phenomena have been explored about the nonparaxial deformation coefficients of the laser beam wavefront. Due to the relativistic nonlinear interaction between the nonparaxial laser beam and plasma, a self-focused laser beam will have appeared. The proper differential equations relating to the behavior of the laser beam inside plasma have been obtained, and they have been numerically solved by creating the appropriate Matlab algorithms. The results demonstrate that as both nonparaxial deformation coefficients are decreed, the self-focusing of the laser beam increases, however, the second-order spherical deformation coefficient is bigger than the fourth-order spherical deformation coefficient. This study also explores the relationship between laser beam intensity, plasma frequency, and laser beam diameter on the laser beam's ability to self-focus inside the plasma. When these factors are sufficiently high, a laser beam with a high degree of self-focusing will be visible. At low magnitudes, however, the phenomena of a laser beam defocusing will predominate.

**2023, 33 pages**



**Keywords:** Relativistic, Nonparaxial coefficients, Plasma density

# ÖZET

## YÜKSEK YOĞUNLUKLU LAZER IŞINININ PARAKSİYEL OLMAYAN KATSAYILARININ PLAZMA İÇİNDEKİ GÖRECELİ KENDİ KENDİNE ODAKLANMA ÜZERİNDEKİ ETKİSİ

Fatimah Dhari Jabbar AL-KHRAYFAWEE

Fizik, Yüksek Lisans

Tez Danışmanı: Prof. Dr. Çiğdem YÜKSEKTEPE ATAOL

Eş Danışman: Prof. Dr. Munther Baqir HASSAN ALKHAQANI

Haziran 2023

Bu tezde, lazer ışını dalga cephesinin paraksiyel olmayan deformasyon katsayıları hakkında kendi kendine odaklanma olgusu araştırılmıştır. Paraksiyel olmayan lazer ışını ve plazma arasındaki göreceli doğrusal olmayan etkileşim nedeniyle, kendi kendine odaklanan bir lazer ışını ortaya çıkacaktır. Lazer ışınının plazma içindeki davranışına ilişkin uygun diferansiyel denklemler elde edilmiş ve uygun Matlab algoritmaları oluşturularak sayısal olarak çözülmüştür. Sonuçlar, her iki paraksiyel olmayan deformasyon katsayısı azaldıkça, lazer ışınının kendi kendine odaklanmasının arttığını, ancak ikinci dereceden küresel deformasyon katsayısının dördüncü dereceden küresel deformasyon katsayısından daha büyük olduğunu göstermektedir. Bu çalışma ayrıca lazer ışınının plazma içinde kendi kendine odaklanma yeteneği üzerinde lazer ışını yoğunluğu, plazma frekansı ve lazer ışını çapı arasındaki ilişkiyi araştırmaktadır. Bu faktörler yeterince yüksek olduğunda, yüksek derecede kendi kendine odaklanma özelliğine sahip bir lazer ışını görülebilecektir. Buna karşın düşük büyüklüklerde lazer ışınının odaktan çıkması olgusu baskın olacaktır.

**2023, 33 sayfa**

**Anahtar Kelimeler:** Göreceli, Paraksiyal olmayan katsayılar, Plazma yoğunluğu

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I would like to thank all those who have helped my teachers, colleagues and wish them success.

**Fatimah Dhari Jabbar AL-KHRAYFAWEE**

**Çankırı-2023**

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## LIST OF SYMBOLS

| | |
|---|---|
| $f_0$ | A laser beam width parameter |
| $A_0$ | Amplitude of linearly polarized laser |
| $\vec{A}_0$ | Amplitude of right circularly polarized laser |
| $S_{00}$ | Beam width parameter |
| $\varepsilon_{eff}$ | Effective dielectric constant |
| $e$ | Electron charge |
| $m_o$ | Electron mass |
| $\upsilon_0$ | Electron oscillation speed in a laser electric field |
| $\omega_o$ | Frequency of laser beam |
| $A_0^*$ | Imaginary amplitude of the right circularly polarized laser |
| $I$ | Laser intensity |
| $\alpha_{00}$ | Normalized amplitude parameter (laser strength parameter) |
| $\vec{\upsilon}$ | Oscillatory velocity of the electron in laser electric field |
| $S$ | Phase function of the amplitude of the linearly polarized laser |
| $\omega_p$ | Plasma frequency |
| $\omega_{\mathrm{ep}}$ | Plasma frequency of electrons |
| $A_0^0$ | Real function of the amplitude of right circularly polarized |
| $\varepsilon_2$ | Relativistic part of dielectric constant |
| $\alpha_{02}$ | Spherical deformation coefficients from r4 |
| $\vec{E}_0$ | Vector of the laser electric field |
| $k_0$ | Wave number of linearly polarized light |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| FWHM | Full width at half maximum |
| HGB | Hollow Gaussian beam |
| HGLB | Hollow Gaussian laser beam |
| OAM | Orbital angular momentum |
| TEM | Transverse electromagnetic |
| WKB | Wentzel-Kramers-Brillouin |

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# 1. INTRODUCTION

Nowadays more efforts have been focused by researchers on the nonlinear interaction between laser and plasma in both experimental and theoretical scopes (Snyder *et al.* 2020). Due to the diffraction behavior of laser beam (as a solid state laser or semiconductor injection laser) through its propagation in media, so more attention in the past attracted to investigating the movement of the laser beam in the non-paraxial area (Jee *et al.* 1988). The internal, self-focusing laser beam media may be considered one of the common and important phenomena. The designers of laser systems try to avoid the self-focusing effect because it may damage the laser active media (Chen *et al.* 2020, Pritula *et al.* 2000). The self-focusing effect has been applied to many applications in laser plasma nonlinear interactions, including inertial confinement fusion, the production of high order harmonics, the acceleration of charged particle beams by laser plasma coupling, and coherent THz emission (Hassan *et al.* 2019, Punia and Malik 2019, Panwar and Sharma 2018). Hassan and Madhi (2018) investigated the ability of ponderomotive nonlinearity to focus a nonparaxial laser beam into a magnetized plasma. They discovered that as the initial laser diameter was increased, the laser beam became more self-focused.

## 1.1 Laser Characteristics

The following are some of the most significant characteristics that set the laser apart and contributed to its significance for scientific investigation, including non-linear interactions between laser and plasma:

### 1.1.1 Directionality

This is a crucial characteristic of the laser beam since we have a little separation between the edge of the beam and its axis, which can be overlooked in some linear studies. The laws of the angle of deviation are used to determine the angle (Sharma and Kourakis 2010). The radiation extends at a specified divergence angle ($\theta$), when mixed with other electromagnetic radiation, the angular extension of this laser beam is practically negligible, and its slight deletion angle usually serves to differentiate it.

### 1.1.2 Monochromatic

This implies that light has a single wavelength rather than several. In contrast to regular light, which has a variety of colors and wavelengths and eventually diverse and multiple energies, laser light is distinguished by this quality (Träger 2012). The frequency, energy, and wavelength of every photon produced as laser light are the same. Laser light has a relatively narrow band of wavelengths or frequencies that it can cover.

### 1.1.3 Coherence

One of its properties demonstrates that waves are capable of interfering with one another. As long as they remain in phase with one another, light waves appear to be coherent. If the light beam turns out to have an internal arrangement, the four light waves are enclosed inside a highly parallel pulsed laser. Coherence comes in two flavors: temporal and spatial (O'Shea *et al.* 1978). Types of a-spatial coherence and b-temporal coherence are depicted in Figure 1.1. The two locations P and Q at the front of the electromagnetic wave will have the same phase difference at the same moment $t = 0$ if the phase difference continues.

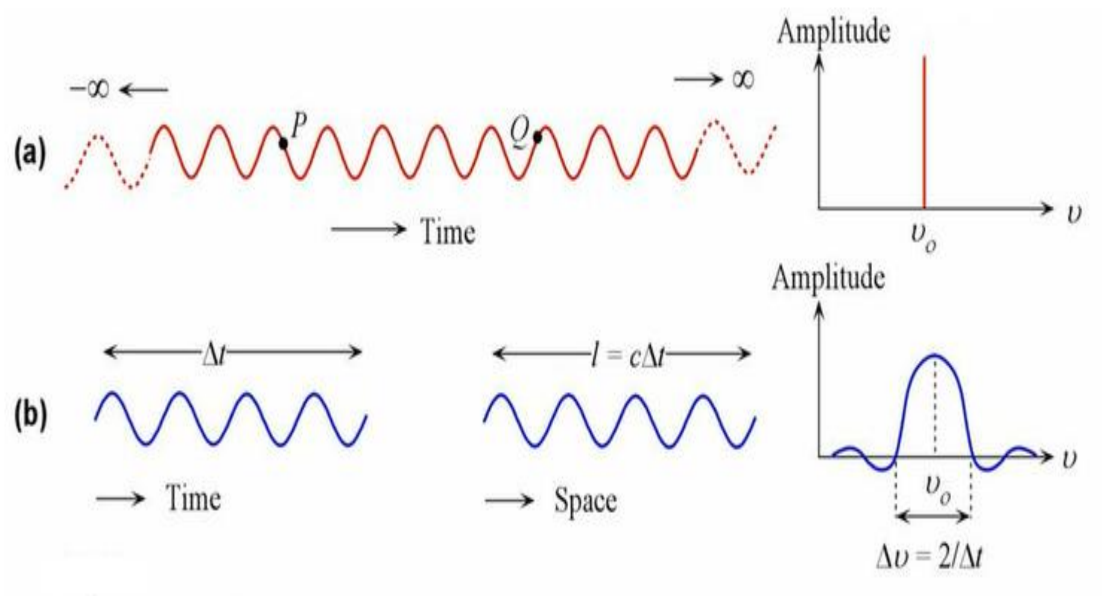


**Figure 1.1** It is argued that the waves in the spatial coherence are continuous beyond the period $t\rangle 0$. If either, then the two front dots of the electromagnetic vector have different phases, with t=0. Any time the phase difference was constant. It is alleged that the temporal coherence waves can be seen (Eichhorn 2014)

## 1.2 Plasma Properties

A gas called plasma contains the vast majority of atoms that have been ionized, demonstrating a collective behavior (Sturrock 1994).

Basic Plasma: A variety of plasma features can be investigated since they react to a collection of charged particles with electromagnetic force (Chen 1984).

### 1.2.1 Temperature

Before continuing, it might be best to consider and clarify our current understanding of "temperature" in terms of the physical world. Similar to the Maxwellian distribution, the most probable distribution of these velocities in gas in thermal equilibrium is referred to. Consider a gas where, for the sake of simplicity, each particle can only travel in one direction. This is not entirely illogical; for instance, electrons always travel along the lines of a strong magnetic field.

Given the Maxwellian distribution in one dimension, where the components of the one-dimensional Maxwellian function are the electron mass, the average particle speed, and the strength of the electric field. Temperatures must always be represented in terms of energy in plasma physics. To minimize confusion, the energy associated with KT, which is used to describe temperature, should be used instead of the number of dimensions involved. Because we have the fact that plasma can have multiple temperatures at once is intriguing. The temperature T of the ions and electrons' Maxwellian distributions are frequently different from one another. This occurs because the rate of collisions between an ion and an electron is higher than the rate of collisions between ions or among electrons themselves. Many species can then be independent states of thermal equilibrium, however, the plasma might not be in it survive long enough for between the two temperatures balance. An individual species, let's Ions, for example, can have two temperatures, when there is a magnetic field B. This is because an ion is subject to forces parallel to B (due to the Lorentz force) that are different from those acting perpendicular to B.

### 1.2.2 Debye length

The Debye length is a measurement of the Boltzmann constant, electron density, electron temperature, and the thickness of the reserved electron shell (Dendy 1995).

Because each layer of plasma includes more electrons, it is important to note that as density rises, it falls, as one might anticipate. It also gets bigger when the increase gets bigger. The charge cloud would become infinitely thin without thermal stimulation. Additionally, as electrons are more mobile than ions and frequently move to produce an excess or deficit of negative charge, the electron temperature is included in the definition. This is only false in a few unique circumstances (Chen 1984). To the plasma's actual size, the Debye sifting length is small. According to this criterion, interactions within the plasma's central region compared to those at its boundaries, where potential boundary effects may occur, are more substantial and manifest. The plasma is nearly neutral when this requirement is met (Hazeltine and Waelbroeck 2004).

### 1.2.3 Plasma frequency

The regularity of circular motion in collective charged particle oscillations under self-steady (Gibbon *et al.* 2011), when compared to the measurement frequency of the neutral electron collision frequency for collisions between electrons and neutral particles, the frequency of the electron plasma that tracks the electron plasma oscillations are much higher. When in comparison to the measurement how frequently the neutral electron collision frequency for collisions between electrons and neutral particle, the frequency of the electron plasma that tracks the electron plasma oscillations are very frequent (Hazeltine and Waelbroeck 2004).

Plasma is one of the best media for nonlinear interactions with lasers, and when we talk about density, we usually mean electron density, or the number of free electrons in a given volume. Plasma is an ionized gaseous medium, which allows for the utilization of large densities without the medium degrading.

## 1.3 Nonlinear Forces in Laser Plasma Interactions Self-Focusing

A nonlinear laser beam can self-focus in plasma by three primary mechanisms: thermal nonlinearity, nonlinearity in relativity, and speculative nonlinearity (Hassan and Soary 2014). Each of them is influenced by the process's time scale, which in our instance is the laser pulse's duration (Liu and Tripathi 1994).

**Kinetic nonlinearity:** This generation is possible as long as the ions' sound speed and the laser beam's size (measured in FWHM) are both equal.

**Thermal nonlinearity:** during the pulse duration higher than or equal to the time it takes for the energy of the electrons (carriers) to relax, like in the ionosphere, this nonlinear display occurs.

**Relativistic nonlinearity:** Two conditions for applying nonlinear relativity will be satisfied when utilizing an ultra-short pulsed laser. The first step would be to create a strong laser that would cause the electrons to vibrate with relativistic velocity. Unlike relativistic nonlinearity, which second with rational nonlinearity will be minimized (Figure 1.2).

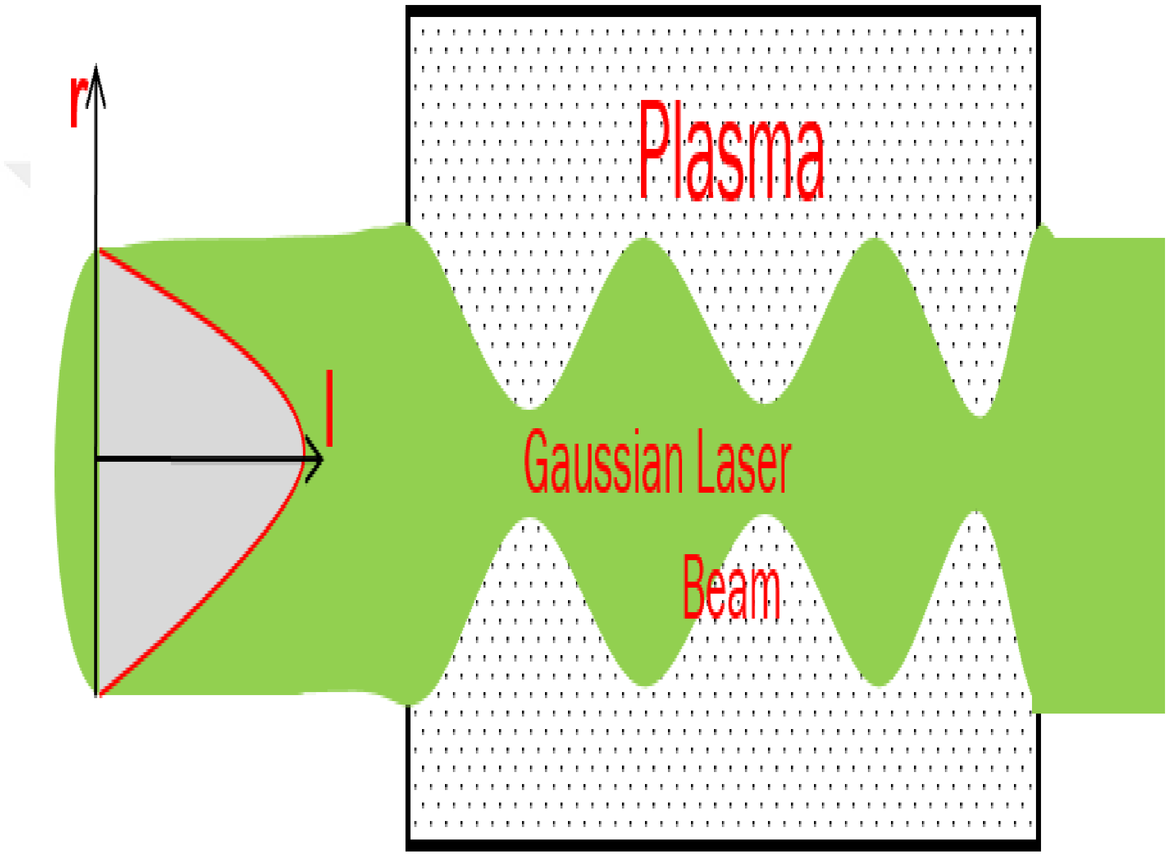


**Figure 1.2** Self-focusing mode of Gaussian laser beam through plasma

## 1.4 Waves in Plasma

According to Table 1.1, the most significant waves that develop in plasma whether a magnetic field is present or not include the ion acoustic wave, plasma oscillation, X wave, magneto sonic wave, light wave, etc (Liu and Tripathi 1986).

**Table 1.1** The elementary plasma waves with their dispersion relation formulas (Liu and Tripathi 1986)

| **EM character** | **Oscillating species** | **Conditions** | **Dispersion relation** | **Name** |
|---|---|---|---|---|
| Electrostatic | Electrons | $\vec{B}_o = 0$ <br> $or\ \vec{K} // \vec{B}_o$ | $\omega_o^2 = \omega_p^2 + \left(\frac{3}{2}\right) K^2 v_{th}^2$ | Plasma oscillation or (Langmuir wave) |
| | | $\vec{K} \times \vec{B}_o$ | $\omega_o^2 = \omega_p^2 + \omega_c^2 = \omega_u^2$ | upper hybrid oscillation |
| | Ions | $\vec{B}_o = 0$ <br> or $\vec{K} // \vec{B}_o$ | $\omega_o^2 = K^2 C_s^2 = K^2 \frac{\gamma_e K_B T_e + \gamma_i K_B T_i}{m_i}$ | ion acoustic wave |
| | | $\vec{K} \perp \vec{B}_o$ <br> (nearly) | $\omega_o^2 = \omega_{ci}^2 + K^2 C_s^2$ | electrostatic ion cyclotron wave |
| | | $\vec{K} \perp \vec{B}_o$ <br> (exactly) | $\omega_o^2 = \omega_i^2 = \omega_{ci}\omega_c$ | lower hybrid oscillation |
| Electromagnetic | Electrons | $\vec{B}_o = 0$ | $\omega_o^2 = \omega_p^2 + K^2 c^2$ | light wave |
| | | $\vec{K} \perp \vec{B}_o, \vec{E} // \vec{B}_o$ | $\frac{c^2 K^2}{\omega_o^2} = 1 - \frac{\omega_p^2}{\omega_o^2}$ | 0 wave |
| | | $\vec{K} \perp \vec{B}_o, \vec{E} // \vec{B}_o$ | $\frac{c^2 K^2}{\omega_o^2} = 1 - \frac{\omega_p^2}{\omega_o^2} \frac{\omega_o^2 - \omega_p^2}{\omega_o^2 - \omega_u^2}$ | X wave |
| | | $\vec{K} // \vec{B}_o$ <br> (right circ. Pol.) | $\frac{c^2 K^2}{\omega_o^2} = 1 - \frac{\omega_p^2 / \omega_o^2}{1 - (\omega_c / \omega_o)}$ | R wave (whistler mode) |
| | | $\vec{K} // \vec{B}_o$ <br> (left circ. Pol.) | $\frac{c^2 K^2}{\omega_o^2} = 1 - \frac{\omega_p^2 / \omega_o^2}{1 + (\omega_c / \omega_o)}$ | L wave |
| | Ions | $\vec{B}_o = 0$ | | None |
| | | $\vec{K} // \vec{B}_o$ | $\omega_o^2 = K^2 v_A^2$ | Alfven wave |
| | | $\vec{K} \perp \vec{B}_o$ | $\frac{\omega_o^2}{K^2} = c^2 \frac{C_s^2 + v_A^2}{c^2 + v_A^2}$ | Magnetosonic wave |

## 1.5 Laser Transverse Modes

The laser beam cross-sectional areas dispersion of laser intensity appears in several shapes namely transverse modes of laser or transverse electromagnetic waves (TEM).

### 1.5.1 Gaussian laser mode $TEM_{00}$

The Gaussian beam, which can also refer to a Gaussian power profile, is a monochromatic electromagnetic radiation beam with a magnetic width and an electric field strength profile provided by the Gaussian property. In some laser optics systems, the laser beam is predicted to be Gaussian and has a radiation profile that matches the ideal Gaussian distribution. An ideal Gaussian behavior and an actual laser can behave differently. We compare the output of a genuine laser beam with that of a skewed Gaussian beam using the M factor, or beam quality factor (Sutherland 2003). For a given wavelength and polarization, the so-called waist circumference of some of this circular Gaussian beam's electric and magnetic field amplitude profiles is governed by a single quantity (Bandres and Gutiérrez-Vega 2004). Due to its regular round shape and homogeneous pattern, the $TEM_{00}$ Gaussian beam is crucial in this process. With little diffraction, density is evenly spread from the center to the edges. Additionally, it possesses 85% of the power within a laser beam. The Gaussian beam is the best in applications due to these characteristics (Boyd and Masters 2009) (Figure 1.3).

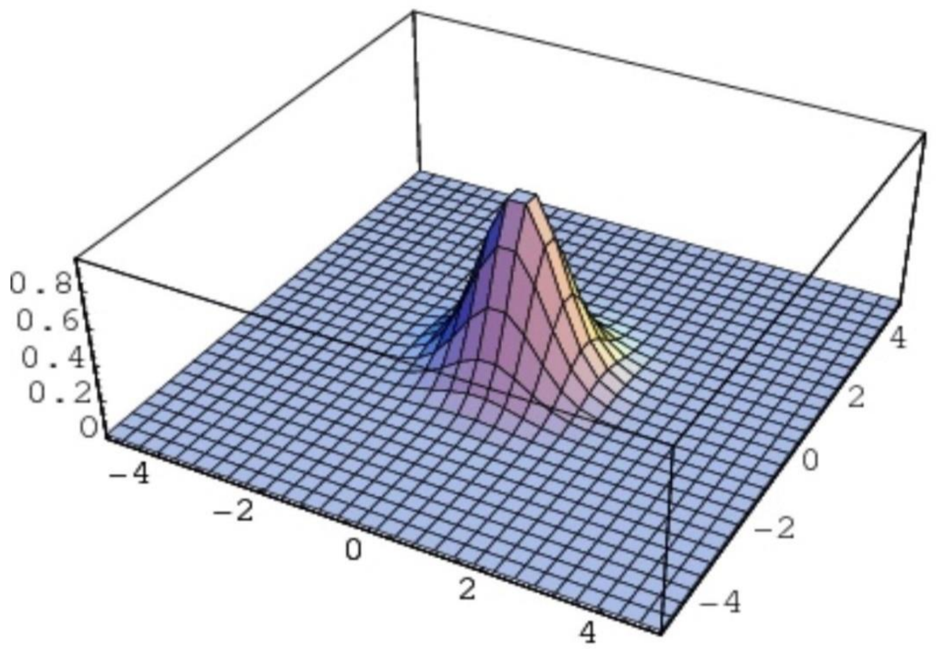


**Figure 1.3** Gaussian function (Weisstein 2002)

### 1.5.2 Hollow Gaussian laser beam (HGLB) ($TEM_{10}$)

A unique type of doughnut-shaped beams called hollow Gaussian beams (HGB) lacks Angular momentum in orbit (OAM). These A beam has numerous uses in a variety of disciplines, such as atmospheric science, bio-photonics, plasma physics, and atomic optics (Chaitanya *et al.* 2016). The hollow Gaussian beam (HGB) was first introduced twenty years ago. In a magnetic plasma, two powerful hollow Gaussian laser beams (HGLBs) operating at various frequencies are examined analytically and numerically by Cai *et al.* (2003). This work was done while a that which is relativistic nonlinearity is dependent based on how powerful the two laser beams are was present. Cross-focusing, a process where the actions of a single laser beam influence the behavior of a different laser beam, is used to explain two laser beams moving across a plasma in this process. HGLB beamwidth nonlinear differential equations were developed utilizing high-level axis theory and a technique called Wentzel-Kramers-Brillouin (WKB). The HGLBs' maximum irradiance was used to derive the phrase for the plasma dielectric constant that is nonlinear (Purohit *et al.* 2022) (Figure 1.4).

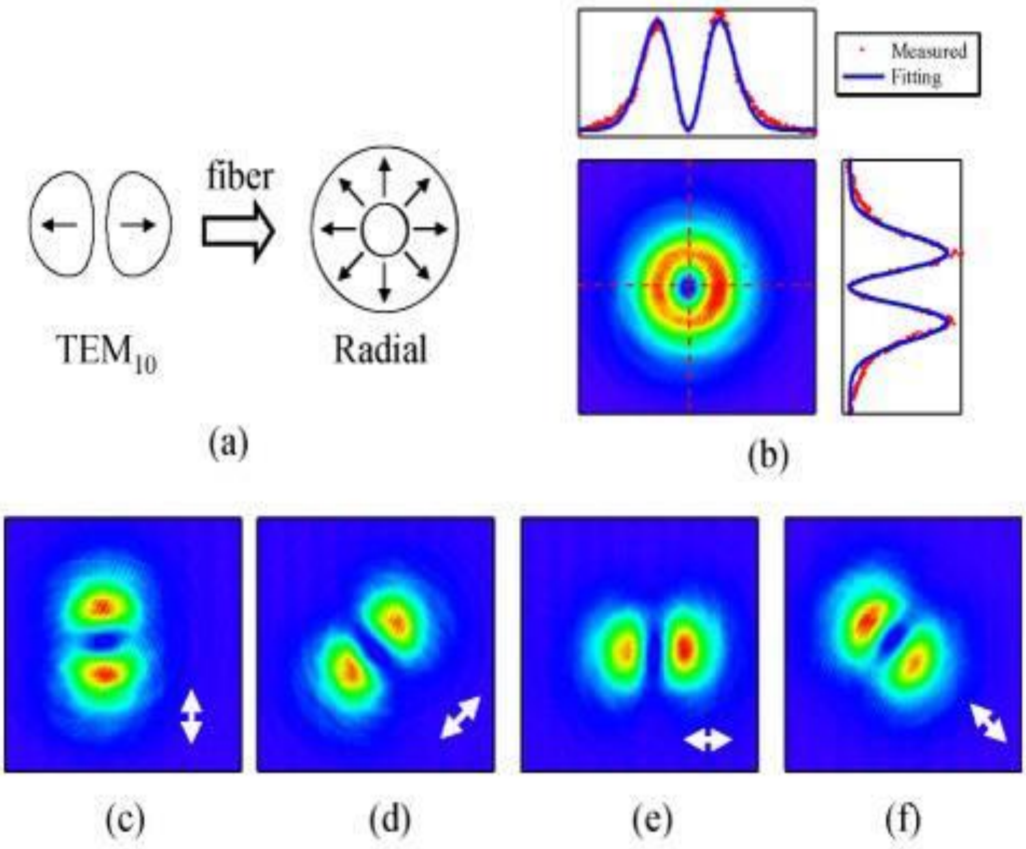


**Figure 1.4** (a) Schematic drawing of conversion from a $TEM_{10}$ mode beam to a radially polarized beam (b) Observed total intensity distribution and the intensity profile (c)–(f) Intensity distributions after passing through a linear polarizer. Each arrow indicates the direction of the polarizer (Hirayama *et al.* 2006)

### 1.6 The Propagation of Laser Beam in non Paraxial Region

An axial Gaussian ray, a ray, violates the Helmholtz equation. This conclusion was obtained directly from Maxwell's equations without any approximations.

The axial approximation of the Fresnel diffraction principle permits inaccurate.

Beam divergence occurs when laser beams move through any medium. This divergence is a characteristic of the beams rather than an abnormal condition. In the majority of studies, the semi-axial region was taken into consideration while considering short-term diffusion, and a more practical theory was utilized in the long term, the semi-axial theory (Kumar and Tripathi 2006). The non-axial state of the rays, which is the state we concentrate on in our study, is the situation that is most likely to occur in reality. Semi-axial rays, which are an example of non-paraxial rays and may be seen in Figure 1.5, are regarded to be the ideal state for rays (Hazarika *et al.* 2019).

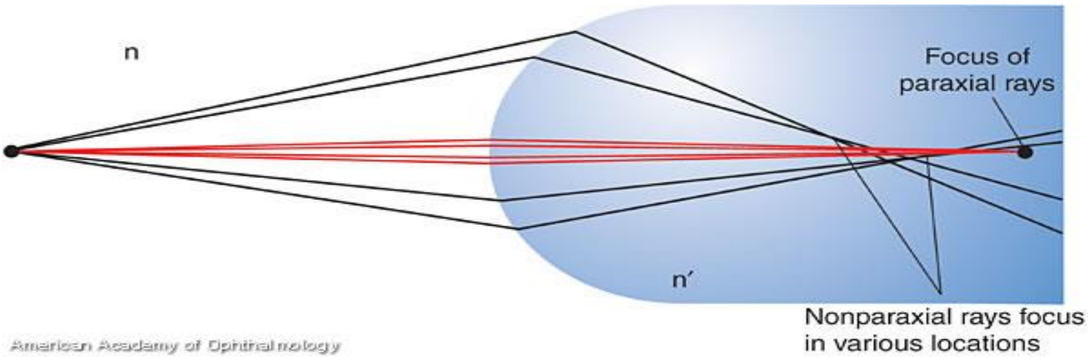


**Figure 1.5** Paraxial and non-paraxial rays in various locations (Hazarika *et al.* 2019)

### 1.6.1 Rayleigh length

The range that runs parallel to the direction of laser beam propagation from the waist to the extent that the cross-section is the region is as much as two cross-section regions is known as the Rayleigh range or length (Meschede 2017). Equation (1.1) and Equation (1.2) illustrate for a Gaussian beam spreads out along the (z) axis, which is given by its Rayleigh length (Figure 1.6).

$$Z_R = \frac{\pi W^2}{\lambda} \tag{1.1}$$

$$\lambda = \frac{2\pi c}{\omega} \tag{1.2}$$

$\omega$ is the laser frequency together $\lambda$ with the laser's wavelength. W is the laser spot radius at focus.

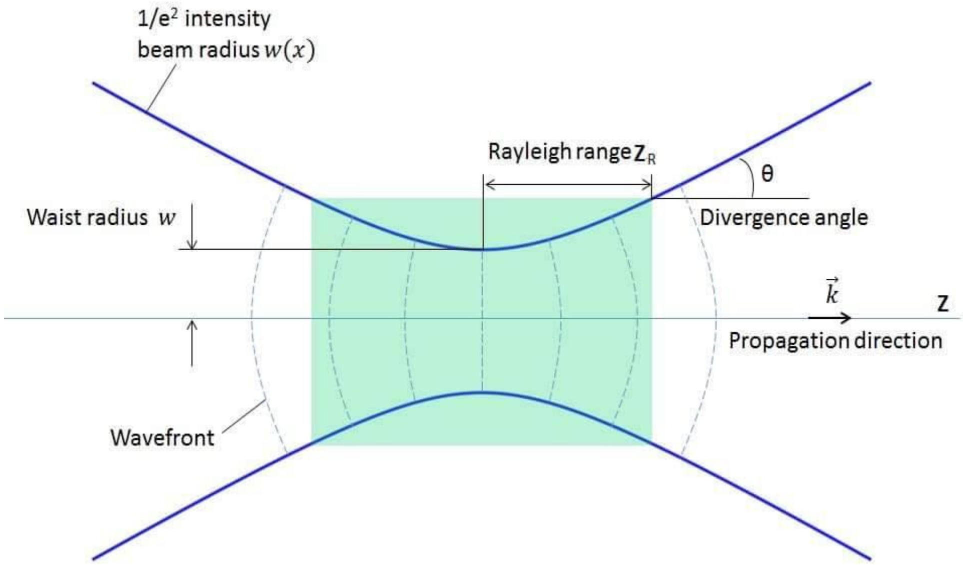


**Figure 1.6** Gaussian beam size about axial distance: beam waist; confocal parameter; length of Rayleigh; total angular dispersion (Meschede 2017)

### 1.6.2 The radius of wavefront curvature

The relationship listed in Equation (1.3) is;

$$R(z) = z\left[1 + \left(\frac{z_\circ}{z}\right)^2\right] \tag{1.3}$$

R(z) is the radius of curvature of the wavefront, and is the Axis of propagation $z_\circ$ at $z = 0$ (Figure 1.7).

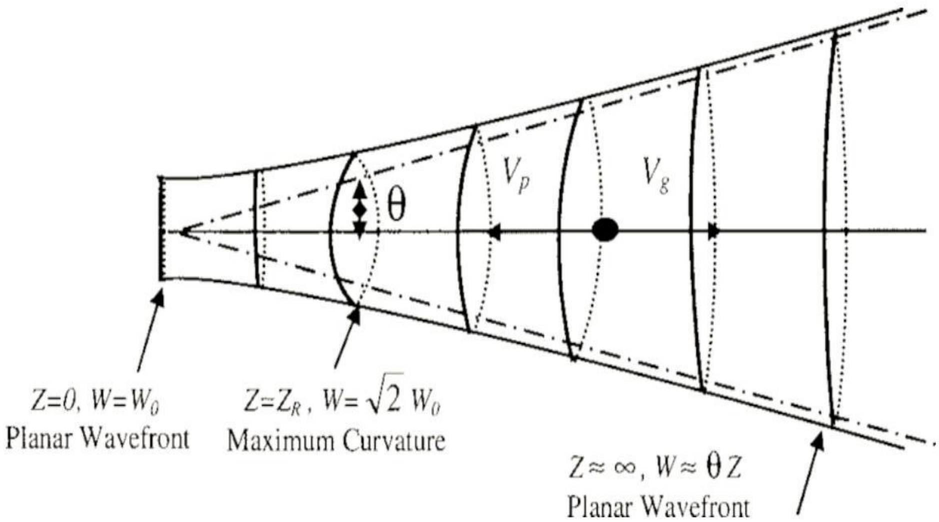


**Figure 1.7** Changes in wavefront radius with propagation distance (Banerjee and Nehmetallah 2006)

### 1.6.3 Divergence angle

It is the degree of optical axis shift in the laser beam. Utilizing the formula in Equation (1.4), the divergence angle is computed (Wei and Yan 2014) (Figure 1.8).

$$\theta = \frac{\lambda}{\pi\omega} \tag{1.4}$$

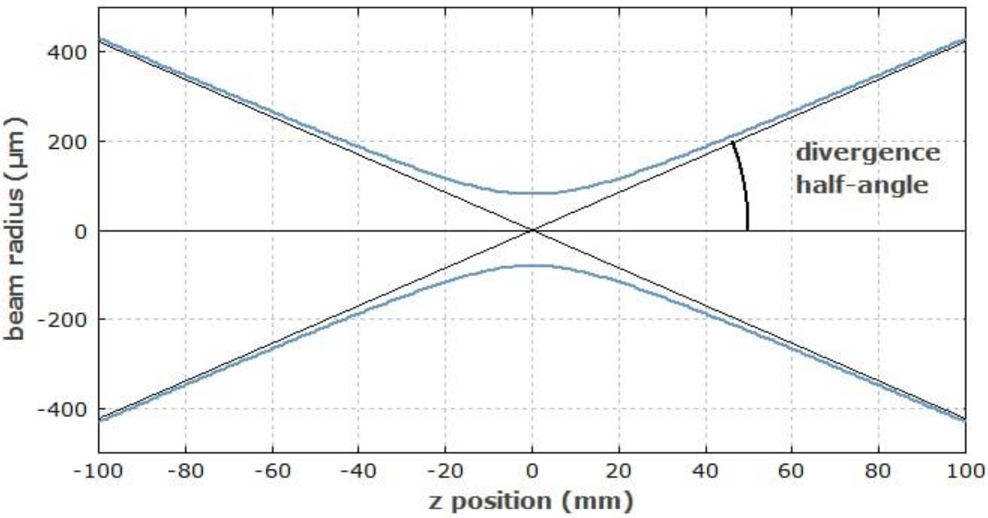


**Figure 1.8** Divergence angle of Gaussian beam propagation (Paschotta 2008)

## 1.7 Development High-Intensity Lasers

Since the invention of the laser, higher-intensity pulses have been produced by it, which is a monument to the inventiveness of science and engineering. Lasers could run on kilowatt-sea pulses in the 1960s. A few years later, the Q switch enabled power production in the MW system. Finally, in 1965, gigawatt pulses were clarified using mode-locking techniques. With such a rapid rate of increase, we should have anticipated that by the end of 196 organizations, when terawatt pulses became feasible, we would need to empirically test the novel phenomena predicted in theory. Unfortunately, it was unable to live up to these early hopes. The gigawatt point has been reached for tiny solid-state laser system peak production (Mourou and Umstadter 1992).

Several different kinds of lasers can generate laser pulses that are brief enough for liquid and solid-state lasers. The link between laser intensity, power, time, and area can be used to reduce pulse time and achieve high intensity. Electric field symbol: E. By using the relation to reduce the laser beam's radius, high-intensity laser light can also be produced. Equation (1.5) shows the continuous autofocus (Webb and Jones, J. D. 2004);

$$I = \frac{P}{A} = \frac{P}{4\pi r^2} \tag{1.5}$$

## 1.8 Laser Plasma Interaction Applications

Since a laser pulse spreads over significant distances and higher laser intensity requires a narrow focus and consequently a short Rayleigh length, there are numerous applications for the plasma-laser nonlinear interaction, particularly the proliferation of intense laser pulses in gasses and plasmas.

### 1.8.1 Plasma accelerator

The plasma is a gas made up of negative electrons and positive ions, when a high-intensity light pulse hits the plasma, it accelerates the electrons to almost the speed of light. It is possible for a powerful electric field to form that can be used to speed up other particles. Conventional accelerators are used to correct radio waves (high-frequency electromagnetic waves) so that charges are repeatedly pushed along the beamline, such as the 3 km Stanford Linear Accelerator.

The Stanford accelerator must be 3 km long for the particles to reach their desired energy. Ultra-strong pulses can accelerate the particles directly like how the beam produces relativistic electrons (Esarey *et al.* 1996).

### 1.8.2 Generation X-rays lasers

X-rays are produced when ultrafast, high-intensity laser flashes collide with a stationary target because they pass through dense plasma while creating them. These X-rays may have a brief pulse duration due to the laser's fleeting encounter with the plasma and the plasma's quick cooling (pico-to-pico-seconds). Recently, it has been demonstrated that one of the key roles in the production of LPX is played by ASE (spontaneous amplified emission). The main pulses are then resonantly absorbed rather than by the core density as the ASE produces a high-density pre-plasma, producing hot plasma electrons. These heated electrons penetrate the solid target and emit both natural X-rays and distinctive X-rays. Therefore, ASE control is required to regulate pre-plasma diffusion. Or, to put it another way, the primary pulses are anticipated to be effectively absorbed into the target near solids where ASE becomes modest. Additionally, the laser plasma contributes a wider variety of hot electrons from the generation of X-rays to the gradually resolved Debye-Scherrer diffraction (Kmetec *et al.* 1992).

### 1.8.3 Harmonic generation

The phenomena can be used to produce short-wavelength radiation of harmonic production via It is being investigated and evaluated how high-intensity laser beams affect electron oscillation. The harmonic creation of asymmetry by scattering the nonlinearity of individual electrons is one example of a straightforward catalyst. This effect of the coherent transcript in plasma under density has been the subject of recent investigations, and it is now being reconsidered. There have been some issues in separating these harmonics from those brought on by the same nonlinear mechanism of electrons that is linked to uncommon and unique types of gas (Gibbon 1997).

## 1.9 The Aim of Study

- This project's primary goal is to investigate the impact of the non-axial coefficients influence of the laser beam and its characteristics (intensity and diameter) on the laser beam's ability to self-focus inside a plasma.
- To study Gaussian laser beam propagation ($TEM_{00}$ mode) through magnetized plasma.
- Investigation of the effect of plasma parameters (plasma frequency and Debye length) on nonlinear propagation and the laser beam examined.
- To examine the impact of non-axial coefficients, laser intensity, and beginning laser beam diameter on the laser's ability to focus on itself in various modes, and to obtain the necessary equations for the $TEM_{00}$ mode of the laser.
- Designing appropriate MATLAB programs to solve the final equations for the laser beam that self-focuses.

## 2. LITERATURE REVIEW

### 2.1 The Self-Focusing Phenomenon of Gaussian Laser Beam Inside Plasma: Nonparaxial Scope

It is important to mention that the dielectric constants of plasma will be changed due to the influence of the high power of the incident laser beam which in role will change the self-focusing of the Gaussian laser beam (Gupta Kumar 2021, Nasser and Hassan 2023). This section will derive the equation of the relativistic dielectric constant and the equation of self-focusing in relativistic plasma.

### 2.2 The Relativistic Dielectric Constant

The motion Equation (2.1) of an electron inside plasma due to a relativistic laser field is written as

$$m_0 \frac{\partial}{\partial t}(\gamma \vec{v}_0 \ (r, y)) = -e\vec{E}_0 \qquad (2.1)$$

where $\vec{E}_0$ represents the electric field of the cylindrically symmetric. Gaussian laser beam propagating along the z-axis through homogeneous plasma which is given as Equation (2.2);

$$\vec{E}_0 = \vec{A}_0(r, z)e^{i(\omega_0 t - k_0 z)} \qquad (2.2)$$

where $\omega_0$ $k_0$ and $\vec{A}_0(x, z)$ are the angular frequency, wave propagation vector, and the amplitude of the electric field respectively.

here $\left( \gamma = (1 - \frac{\upsilon_0^2}{c^2})^{-\frac{1}{2}} \right)$ is the relativistic factor which imparts a relativistic oscillation velocity $\vec{v}_0$ to the plasma electrons which is given as Equation (2.3)

$$\vec{v}_0 = \frac{ie\vec{E}_0}{m_e \gamma \omega_0} \tag{2.3}$$

Depending on Equation (2.2) and Equation (2.3), the relativistic factor γ may be rewritten as Equation (2.4) (Hassan *et al.* 2012);

$$\gamma \cong 1 + \frac{1}{2} \cdot (\frac{e}{m_0 c \omega_0})^2 A_0 \cdot A_0^* \tag{2.4}$$

here $m_0, e,$ and c are the electron rest mass, the electron charge, and the light velocity respectively.

As a result of the nonlinear interaction of high intensity laser beam inside a plasma, a useful dielectric constant $\varepsilon_{eff}$ of plasma will be modified to become as Equation (2.5) (Hassan *et al.* 2012);

$$\varepsilon_{eff} = 1 - \left(\frac{\omega_{pe}}{\omega_0}\right)^2 + \frac{1}{2}\left(\frac{e}{m_0 c \omega_0}\right)^2 \left(\frac{\omega_{pe}}{\omega_0}\right)^2 A_0 A_0^* \tag{2.5}$$

This equation is consisting of two linear and relativistic nonlinear parts Equation (2.6) and Equation (2.7);

$$\text{Linear part } \varepsilon_0 = 1 - \left(\frac{\omega_{pe}}{\omega_0}\right)^2 \tag{2.6}$$

$$\text{Relativistic nonlinear part } \varepsilon_2 A_0 A_0^* = \frac{1}{2}\left(\frac{e}{m_0 c \omega_0}\right)^2 \left(\frac{\omega_{pe}}{\omega_0}\right)^2 A_0 A_0^* \tag{2.7}$$

## 2.3 The Nonparaxial Laser Beam Self-Focusing in Relativistic Plasma

Equation (2.8) regulates the general wave equation of the laser electric field through a plasma medium (Hassan *et al*. 2023):

$$\nabla^2\vec{E}_0 - \nabla(\vec{\nabla}\cdot\vec{E}_0) + \frac{\omega_0^2}{c^2}\underline{\underline{\varepsilon}}\cdot\vec{E}_0 = 0 \tag{2.8}$$

Sodha *et al.* (1974) technique and using Equation (2.5), the generic wave Equation (2.8) can be rewritten as Equation (2.9);

$$\frac{\partial^2 A_0}{\partial z^2} + \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)A_0 + \frac{\omega_0^2}{c^2}(\varepsilon_0 + \varepsilon_2 A_0 A_0^*)A_0 = 0 \tag{2.9}$$

Introducing $A_0 = A_0^0 e^{(ik_0S)} e^{i(\omega_0 t - k_0 z)}$, where $A_0^0$ and $S$ are a real function and the phase function of the laser beam inside plasma respectively, therefore Equation (2.9) can be separated into real and imaginary parts as Equation (2.10) and Equation (2.11);

$$2\frac{\partial S}{\partial z} + \left(\frac{\partial S}{\partial r}\right)^2 - \frac{1}{k_0^2 A_0^0}\left(\frac{\partial^2 A_0^0}{\partial r^2} + \frac{1}{r}\frac{\partial A_0^0}{\partial r}\right) = \frac{\varepsilon_2 (A_0^0)^2}{\varepsilon_0} \tag{2.10}$$

$$\frac{\partial (A_0^0)^2}{\partial z} + (A_0^0)^2\left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r}\right) + \frac{\partial S}{\partial r}\frac{\partial (A_0^0)^2}{\partial r} = 0 \tag{2.11}$$

For the sake of more reality, one may adopt the nonparaxial theory as long as the electromagnetic waves undergo a natural diffraction effect through its propagation inside media. In the nonparaxial region the true function $A_0^0$ as well as the phase function $S$ with relation to the laser beam given as Equation (2.12), Equation (2.13), and Equation (2.14) (Salih *et al.* 2004).

$$A_0^0 = \frac{E_{00}}{f_0}\left(1 + \frac{\alpha_{00} r^2}{r_0^2 f_0^2} + \frac{\alpha_{02} r^4}{r_0^4 f_0^4}\right)^{\frac{1}{2}} e^{\left(\frac{-r^2}{2r_0^2 f_0^2}\right)} \tag{2.12}$$

$$S = \frac{S_{00}}{r_0^2} + \frac{S_{02} r^4}{r_0^4} \tag{2.13}$$

$$S_{00} = \frac{r^2}{2f_0^2}\frac{\partial f_0}{\partial z} \tag{2.14}$$

The beam width setting $f_0$ depicts the variation in the size of the laser beam point as it spreads through the plasma.

It is useful to mention that the second-order spherical deformation coefficient$\alpha_{00}$ and the fourth-order spherical deformation coefficient $\alpha_{02}$ are referring to, respectively, the wavefront's departure from its spherical nature and its spherical curvature. Both $\alpha_{00}$ and $\alpha_{02}$ coefficients are explaining the role of the nonparaxial area in the self-focusing of the laser beam.

Changing Equation (2.8), Equation (2.12), Equation (2.13), and Equation (2.14) in Equation (2.10) and equating the coefficients of order $r^2$and $r^4$of the resulting equation, so one may obtain the Equation (2.15) and Equation (2.16).

$$\frac{d^2 f_0}{dz^2} = \frac{(1-2\alpha_{00}-3\alpha_{00}^2+8\alpha_{02})}{k_0^2 r_0^4 f_0^3} - (1-\alpha_{00})\left(\frac{\varepsilon_2 E_{00}^2}{\varepsilon_0}\right)\frac{1}{r_0^2 f_0^2} \tag{2.15}$$

$$\frac{\partial S_{02}}{\partial z} = \frac{(1-\alpha_{00}+\alpha_{02})\varepsilon_2 E_{00}^2}{2\varepsilon_0 f_0^6} - \frac{(\alpha_{00}^2-7\alpha_{00}\alpha_{02}+\alpha_{00}^2-2\alpha_{02})}{2k_0^2 r_0^2 f_0^6} - \frac{4S_{02}}{f_0}\frac{\partial f_0}{\partial z} \tag{2.16}$$

The last two equations are covering the nonlinear behavior of laser beams in the nonparaxial regions through plasma (Jasim and Hassan 2019). To solve Equation (2.15) and Equation (2.16) completely one may use Equation (2.11) to calculate the variation of the coefficients $\alpha_{00}$ and $\alpha_{02}$ along the z-axis as Equation (2.17) and Equation (2.18).

$$\frac{\partial \alpha_{00}}{\partial z} = -\frac{16 f_0^2 S_{02}}{r_0^2} \tag{2.17}$$

$$\frac{\partial \alpha_{02}}{\partial z} = \left(\frac{8 f_0^2 S_{02}}{r_0^2} - \frac{24\alpha_{00} f_0^2 S_{02}}{r_0^2}\right) \tag{2.18}$$

# 3. MATERIALS AND METHODS

The system of the work consists of a unit of classical plasma (hydrogen plasma) as a nonlinear medium to interact with a Gaussian laser beam produced by Carbon Dioxide ($CO_2$) pulsed laser.

In this study, Matlab programs were designed to numerically solve the differential equations of relativistic self-focusing (Equations 2.15-2.18) based on the Taylor method.

The beamwidth parameter (f) of the laser beam has been normalized at the plasma medium boundary to be ($f=1$). Through laser beam propagation inside the plasma, the value of the beamwidth parameter will be varied to give three distinguished cases:

- $f > 1$ which refers to defocusing or diverging state.
- $f<1$ which refers to the self-focusing or converging state.
- $f=1$ which refers to the waveguiding or channeling state.

# 4. RESULTS AND DISCUSSION

This study is based on the nonlinear interaction between Carbon Dioxide ($CO_2$) pulsed laser, as a pump wave, and hydrogen plasma. The last equations, Equation (2.15), Equation (2.16), Equation (2.17), and Equation (2.18), have been numerically solved from experimental observations using the following set of parameters:

- The angular frequency of Carbon Dioxide ($CO_2$) pulsed laser ($\omega_0 = 1.778 \times 10^{14}\ rad/\text{sec}$) corresponding to the wavelength ($\lambda = 10.6\ \mu m$).
- The initial laser beam intensities are $\left((I = 3.26, 5.35, 6) \times 10^{20}\ W/cm^2\right)$ which are corresponded to the laser strength parameters ($\alpha_r = 0.5, 0.64, 0.68$) where $\alpha_r = \frac{eE_{00}}{m_e \omega_0 c}$ .
- The initial laser beam diameters are $\left((x_0 = 30, 44, 48)\ \mu\text{m}\right)$.
- The plasma densities are ($n_e = (1, 1.9, 2.3) \times 10^{18}\ cm^{-3}$) corresponding to the plasma frequencies $\left({}^{\omega_p}/_{\omega_0} = 0.32, 0.44, 0.48\right)$ or $\left(\omega_p = (5.7, 7.8, 8.5) \times 10^{13}\ rad.\text{sec}^{-1}\right)$

In this research, the effect of the nonparaxial coefficients, laser beam intensity, and initial laser beam diameter on the laser beam self-focusing inside plasma will be demonstrated.

## 4.1 Nonparaxial Coefficients Influence on Laser Beam Self-Focusing

Figure 4.1 and Figure 4.2 explain that the increase of the values of the second-order nonparaxial coefficient ($\alpha_{00} = 0.02, 0.04, 0.06$) and the fourth-order nonparaxial coefficient ($\alpha_{02} = 0.02, 0.04, 0.06$) are leading to decrease the laser beam self-focusing. These results may be interpreted as follows: the wavefront of the laser beam will undergo more curvature as the nonparaxial coefficients are increased thus the focusing ability of the laser beam will become more difficult.

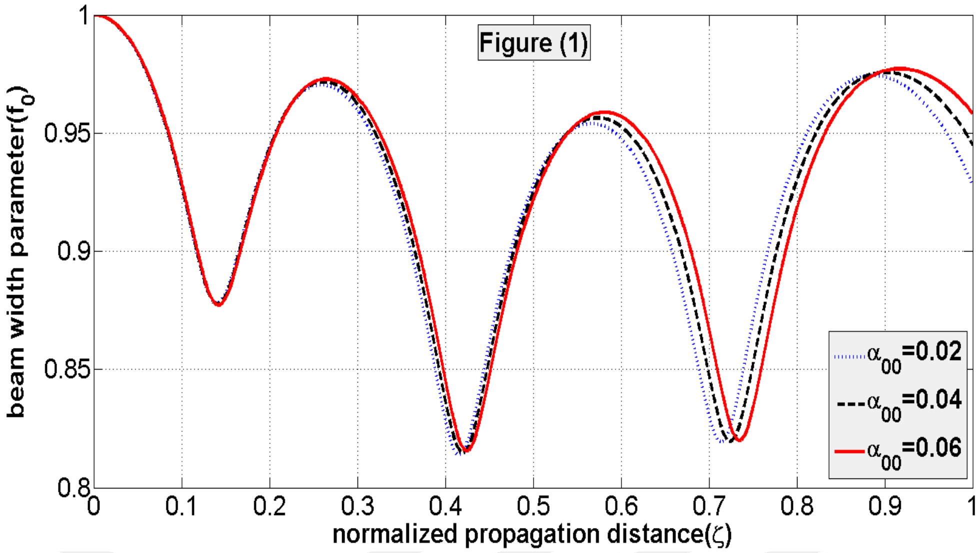


**Figure 4.1** Variation of laser beam width parameter ($\boldsymbol{f_0}$) with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$at different values of the spherical deformation coefficient of second order ($\boldsymbol{\alpha_{00}} = \mathbf{0.02}$ , $\mathbf{0.04}, \mathbf{0.06}$) in the nonparaxial region

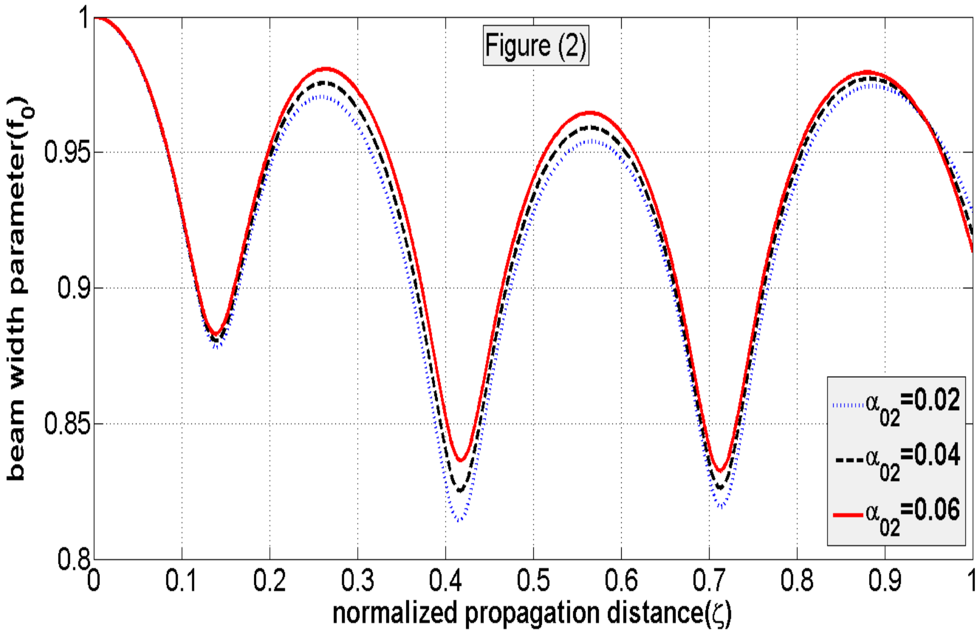


**Figure 4.2** Variation of laser beam width parameter ($\boldsymbol{f_0}$) with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$ at different values of the spherical deformation coefficient of fourth order ($\boldsymbol{\alpha_{02}} = \mathbf{0.02}$ , $\mathbf{0.04}, \mathbf{0.06}$) in the nonparaxial region

Figure 4.3 illustrates self-focusing of the laser beam the presence of a spherical curvature (represented by $\alpha_{00}$ )is greater than the laser beam self-focusing in presence of a nonspherical curvature (represented by $\alpha_{02}$).

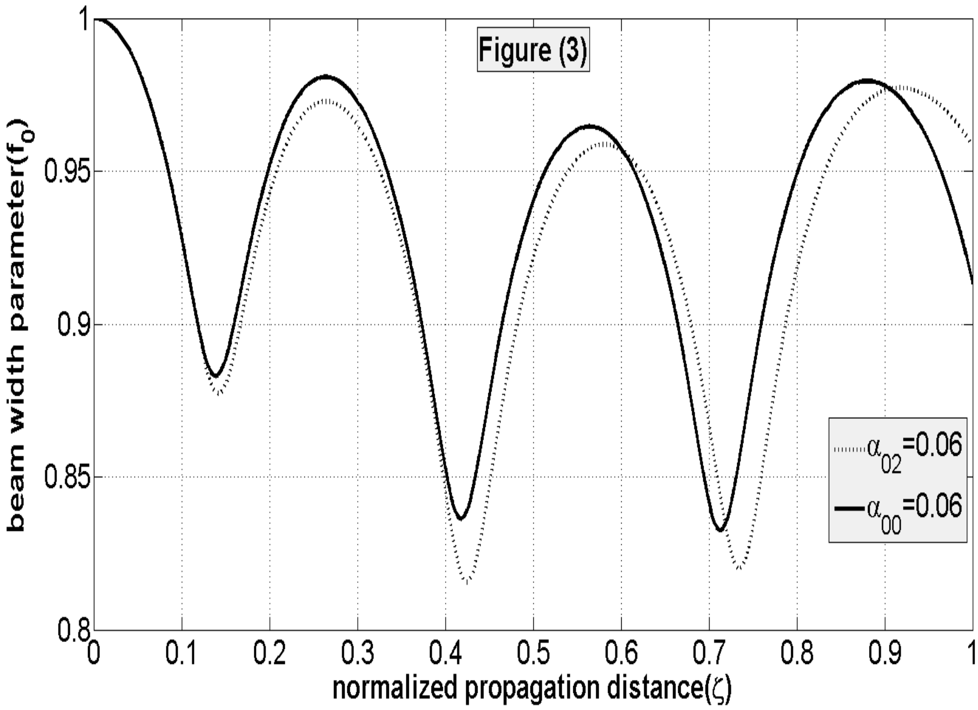


**Figure 4.3** Variation of beam width parameter ($\boldsymbol{f_0}$) with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$, where sold the black line and dotted black line represent ($\boldsymbol{\alpha_{00}} = \mathbf{0.06}$) and ($\boldsymbol{\alpha_{02}} = \mathbf{0.06}$) respectively

## 4.2 Influence of Laser Beam Intensity, Plasma Frequency, and Laser Beam Diameter on Laser Beam Self-Focusing

Figure 4.4, Figure 4.5, and Figure 4.6 one may notice the crucial impact of the laser beam intensity, plasma frequency, and laser beam diameter on the laser beam self-focusing respectively. At low magnitudes of these parameters, the diffraction natural term will overcome the focusing term of the laser beam (see Equation (2.15)). By appropriately increasing these parameter values, namely laser beam intensity, plasma frequency, and laser beam diameter, so one may record a high laser beam self-focusing.

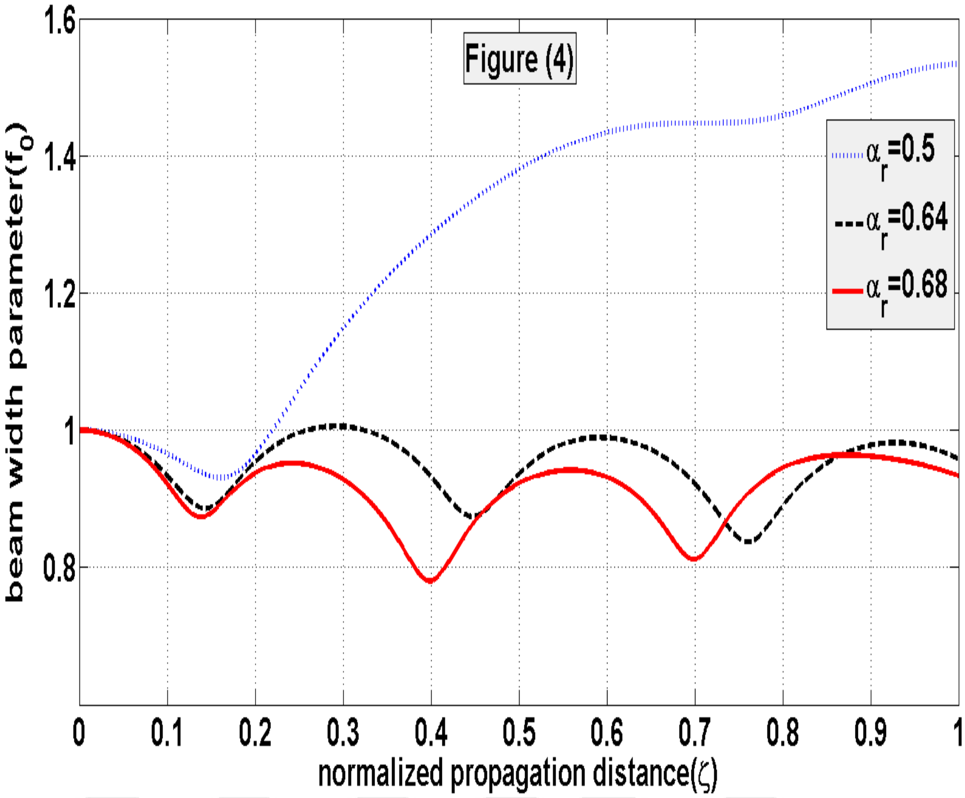


**Figure 4.4** Variation of laser beam width parameter ($\boldsymbol{f_0}$) with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$ at different values of the laser strength parameters ($\boldsymbol{\alpha_r} = \mathbf{0.5}, \mathbf{0.64}, \mathbf{0.68}$) in nonparaxial region($\boldsymbol{\alpha_{00}} = \boldsymbol{\alpha_{02}} = \mathbf{0.02}$)

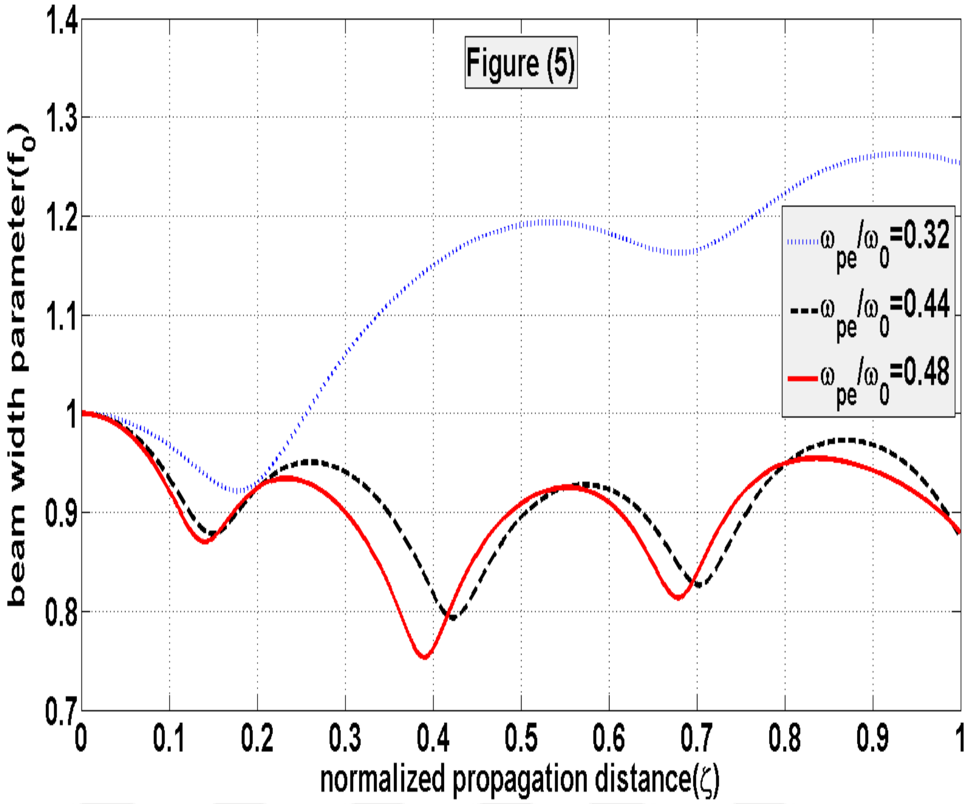


**Figure 4.5** Variation of laser beam width parameter $(\boldsymbol{f_0})$ with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$ at different values of the plasma frequencies $(\boldsymbol{\omega_{pe}} = \mathbf{0.32}\boldsymbol{\omega_0},\ \mathbf{0.44}\boldsymbol{\omega_0},\ \mathbf{0.48}\boldsymbol{\omega_0})$ in nonparaxial region

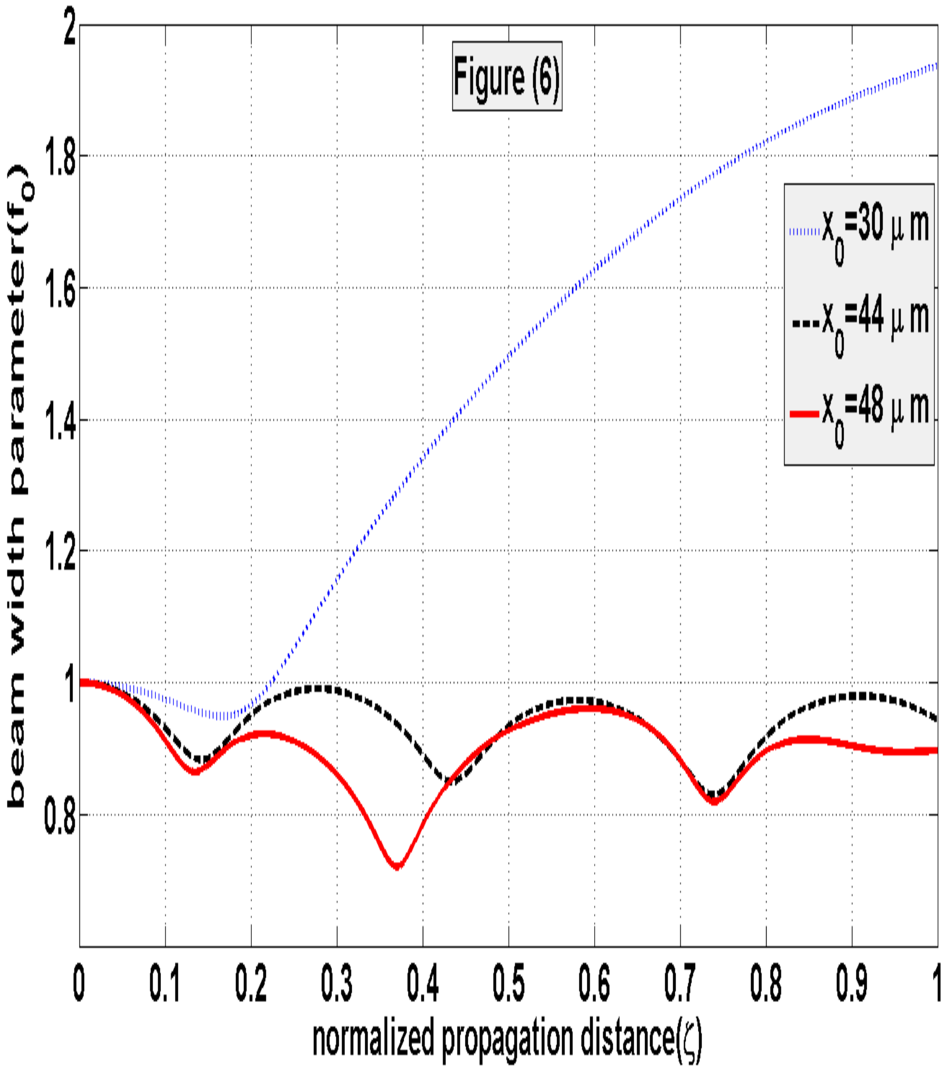


**Figure 4.6** Variation of laser beam width parameter ($\boldsymbol{f_0}$) with normalized distance $\left(\boldsymbol{\zeta} = \frac{\boldsymbol{z}}{\boldsymbol{k_0 x_0^2}}\right)$ at different values of the laser beam diameters ($\boldsymbol{x_0} =$ $\boldsymbol{30\mu}$m, $\boldsymbol{44\mu}$m, $\boldsymbol{48\mu}$m ) in nonparaxial region ($\boldsymbol{\alpha_{00} = \alpha_{02} = 0.02}$)

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

When Plasma is traversed by a high-intensity laser beam, so it will undergo a relativistic nonlinear interaction. This nonlinear behavior will manifest as a self-focusing phenomenon (Purohit *et al.* 2020, Rawat and Purohit 2019). The results have to explain that the self-focusing of the laser beam in the nonparaxial region is increased strongly with decreasing of deformation coefficients ($\alpha_{00}$, $\alpha_{02}$) (Hassan and Madhi (2018). The effect of the spherical deformation coefficient of second order ($\alpha_{00}$) on the laser beam self-focusing is greater compared with the spherical deformation coefficient of fourth order ($\alpha_{02}$). This refers to the spherical curvature due to ($\alpha_{00}$) variation playing a high role in laser beam self-focusing in comparison with nonspherical curvature ($\alpha_{02}$) variation. The laser beam intensity, plasma frequency, and laser beam diameter have very important effects to control and guide the laser beam propagation inside plasma to give rise to a self-focusing phenomenon.

## 5.2 Recommendations

In most laser plasma nonlinear interactions, the effect of the redistribution of electrons inside plasma must be taken into account. This effect will create what is known as ponderomotive nonlinearity. So, for more reality, it is important to expand the theory of the laser plasma nonlinear interaction to include the mutual effects of relativistic nonlinearity and ponderomotive nonlinearity.

Most researchers have focused on the fundamental laser mode (Gaussian laser mode $TEM_{00}$) but fewer them have studied the other laser modes such as Hollow Gaussian laser beams, elliptic Gaussian beams, Hermite–Gaussian beams, and Cosh-Gaussian laser beams. Therefore, it is worthwhile to advise studying these other laser modes.

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## CURRICULUM VITAE

### Personal Information

Name and Surname : Fatimah Dhari Jabbar AL-KHRAYFAWEE

### Education

| | | |
|---|---|---|
| MSc | Çankırı Karatekin University<br>Graduate School of Natural and Applied Sciences<br>Department of Physics | 2020-2023 |
| Undergraduate | University of Kufa<br>Faculty of Education for Girls<br>Department of Physics | 2016-2020 |