Eur. Phys. J. D **17**, 395–398 (2001)

THE EUROPEAN PHYSICAL JOURNAL D
EDP Sciences

An electromagnetic wave propagation in a non-uniform plasma controlled by EIT

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Received 23 May 2001

Abstract. We investigate the conditions in which the propagation of an electromagnetic wave is changed from transparency to cutoff in a non-uniform plasma. The allowed frequency range of the driving wave is obtained for the case that the probe frequency is above the plasma frequency. The effect of the power of the driving field on the range is analyzed.

PACS. 42.50.Hz Strong-field excitation of optical transitions in quantum systems; multi-photon processes; dynamic Stark shift – 52.35.-g Waves, oscillations, and instabilities in plasmas and intense beams

1 Introduction

Electromagnetically Induced Transparency (EIT) is a technique for eliminating of the effect of a medium on a propagating beam of electromagnetic radiation [1]. This is done in an atomic system by applying two lasers whose frequencies differ by a nonallowed transition of an atom or molecule. As a result, the absorption of a weak probe beam at the resonance frequency can be substantially reduced [2], the refractive index is also modified [3]. For EIT in a uniform plasma, the role of the nonallowed transition of the single atom is replaced by a collective longitudinal plasma oscillation, and the two laser frequency difference is close to the plasma frequency, ω_{p} [4]. For the practical purpose, a non-uniform plasma is proposed and the conditions for EIT in it have been discussed where a weak beam below cutoff can propagate transparently [5].

In this paper, we investigate the conditions under which the propagation of an electromagnetic wave can be changed from transmitting to cut-off in the non-uniform plasma *via* the mechanism of EIT. The issue discussed here is different from the one in previous paper [5], in which the conditions where the propagation of an electromagnetic wave from cut-off to transparency by EIT was discussed.

Since the initial state of the propagation of the probe wave is transparent in the non-uniform plasma, the frequency of the probe beam ω must be higher than the maximum plasma frequency ω_{p0}. To cut the probe beam off in the non-uniform plasma, another wave must be applied, which is defined as the driving field with a frequency ω_{a}. Like the discussions on EIT, we assume that the amplitude of the probe is small and the amplitude of the driving is large.

2 Theoretical analyses

The non-uniform plasma discussed here is a simplification of a positive column of a glow discharge plasma. We simplify the characteristics of the plasma column so that it has a radial distribution of the plasma frequency (proportional to the root of plasma density) as shown in Figure 1. The plasma frequency is non-uniform, which is linearly changed at both side and reaches its maximum value ω_{p0} between B and B' where the electron density is uniform. Also we neglect the effect of the curvature of the column, resulting in a one-dimensional system along the Z-axis.

We begin with the case where the frequency of the probe is above the maximum plasma frequency ω_{p0}. When the probe beam with frequency ω travels in the plasma alone, its propagation constant is [6]:

$$k_0 = \frac{1}{c}\sqrt{\omega^2 - \omega_{\mathrm{p}}^2}. \tag{1}$$

The probe beam can penetrate the plasma because $\omega > \omega_{\mathrm{p0}}$. In order to cut it off, a strong driving field with frequency ω_a is applied. The propagation constant

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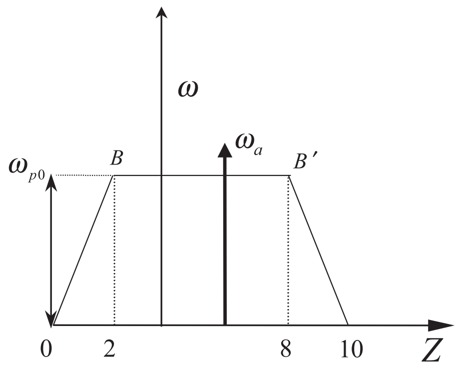

Fig. 1. The plasma frequency ω_p distribution along the propagation direction of the probe wave ω for a non-uniform model. ω_p0 is the maximum value of ω_p. ω_a is the frequency of the strong driving field used to control the propagation of the probe.

of the probe k must satisfy [4]:

$$\frac{(k_\mathrm{a0}^* \mp k)^2}{2}\Lambda\omega_\mathrm{p} - (k_0^2 - k^2)\delta\omega = 0 \tag{2}$$

where $k_\mathrm{a0} = \sqrt{\omega_\mathrm{a}^2 - \omega_\mathrm{p}^2}/c$ is the propagation constant of the driving field if it travels alone; $\delta\omega = \omega_\mathrm{p} - (\omega - \omega_\mathrm{a})$ is the frequency detuning of the plasma frequency ω_p from the longitudinal plasma oscillation frequency $(\omega - \omega_\mathrm{a})$; $\Lambda = (q^2 |E_\mathrm{a}|^2 / 4m\omega_\mathrm{a}^2)/mc^2$ is a constant proportional to the power density of the driving field. The minus and plus sign applies when both waves propagate in the same and opposite direction, respectively. Equation (2) can be expressed as the following equation in terms of characteristic frequencies ω_pole:

$$\omega_\mathrm{pole}(k_\mathrm{a0}^* \mp k)^2 + (k_0^2 - k^2)\delta\omega = 0 \tag{3}$$

where $\omega_\mathrm{pole} = -\Lambda\omega_\mathrm{p}/2$.

The solution of equation (3) is

$$k = \frac{\mp\omega_\mathrm{pole} \pm k_0\sqrt{\delta\omega(\delta\omega - \omega_\mathrm{crit})}}{(\delta\omega - \omega_\mathrm{pole})} \tag{4}$$

where $\omega_\mathrm{crit} = ((\omega^2 - \omega_\mathrm{a}^2)/(\omega^2 - \omega_\mathrm{p}^2))\omega_\mathrm{pole}$ and the plus and minus sign of "$\pm$" in equation (4) applies for $\delta\omega$ below and above the critical frequency, ω_crit, respectively.

Equation (4) reveals that a stop band of the probe beam appears between ω_crit and origin, *i.e.* when $\omega_\mathrm{crit} < \delta\omega < 0$, the probe beam can be cut off. Because the plasma frequency is not uniform, the width of the stop band with different ω_p is various. We depict the curve ω_crit *versus* ω_p in Figure 2 and find that the width of the stop band at ω_p0 has its maximum. Thus we believe that the propagation of the probe beam must be cut off if we apply the width of the stop band at ω_p0 as the value of stop band of the probe beam in the whole non-uniform plasma. That is to say, in the plasma under investigation, when $0 \le \omega_\mathrm{p} \le \omega_\mathrm{p0}$

$$\omega_\mathrm{crit}(\omega_\mathrm{p0}) \le \delta\omega \le 0. \tag{5}$$

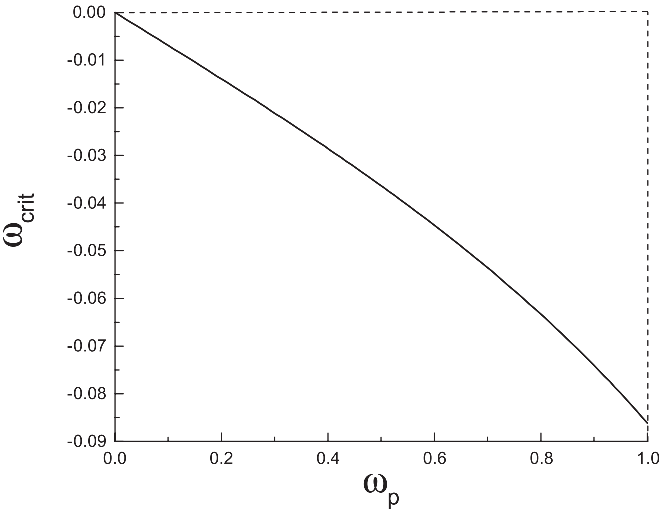

Fig. 2. The curve between the characteristic frequency ω_crit and the plasma frequency ω_p in the non-uniform plasma; the magnitude of ω_crit represents the width of the stop band. The parameters used are $\omega_\mathrm{p0} = 1.0$, $\omega_\mathrm{a} = 1.25$, $\omega = 2.25$, $\Lambda = 0.2$.

In other words,

$$\omega_\mathrm{p0} \le (\omega - \omega_\mathrm{a}) \le \omega_\mathrm{p0} - \omega_\mathrm{crit}(\omega_\mathrm{p0}). \tag{6}$$

In addition,

$$\omega_\mathrm{p0} \le \omega_\mathrm{a} \le \omega - \omega_\mathrm{p0} \tag{7}$$

must be another condition, under which equation (2) is obtained. Equations (6, 7) give the conditions of the driving field in which the propagation of the probe beam can be changed from transparency to cutoff in the non-uniform plasma. It is obvious that the frequency range of the driving field depends on its power Λ.

3 Results and discussion

We analyze the frequency range of the driving field in which the propagation of the probe can be modified. From equation (7), the allowed frequency range of the driving field ω_a *versus* probe frequency ω which is above ω_p0 is shown in the portion covered by solid lines in Figure 3. It shows that the frequency range of the driving field is linearly increased with the frequency of the probe beam to be modified increasing.

We investigate the effect of the power of the driving field on its frequency range, and the result is shown in Figure 4 according to equations (6, 7). The covered portion is the range in which the propagation of the probe wave can be changed from transparency to cutoff. Figure 4 shows that the large range is obtained with the large power parameter Λ in the area covered by the solid lines. When Λ reaches a value marked Λ_0 in Figure 4, the range is expressed as the area covered by dotted lines, which is independent of the value of the power of the driving field.

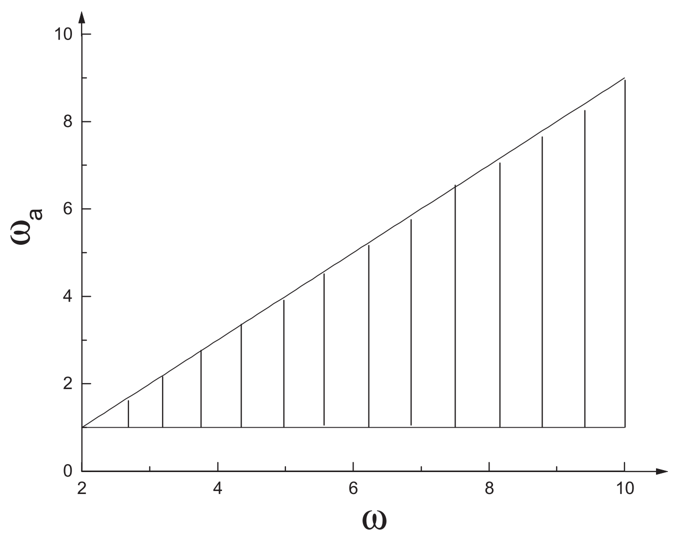

Fig. 3. The range of driving field frequency *versus* the probe frequency. The part covered by the solid lines is the possible range in which the propagation of the probe wave changes from transparency to cut-off. The parameter used is $\omega_{p0} = 1.0$.

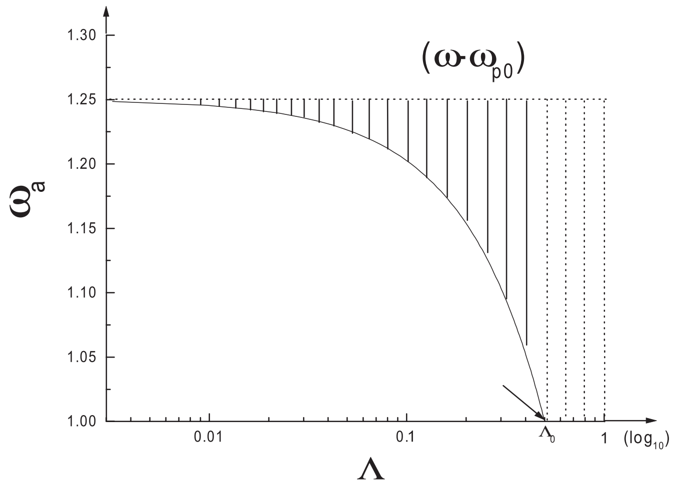

Fig. 4. The frequency range of driving field *versus* the power. The parameters used are $\omega_{p0} = 1.0$, $\omega = 2.25$.

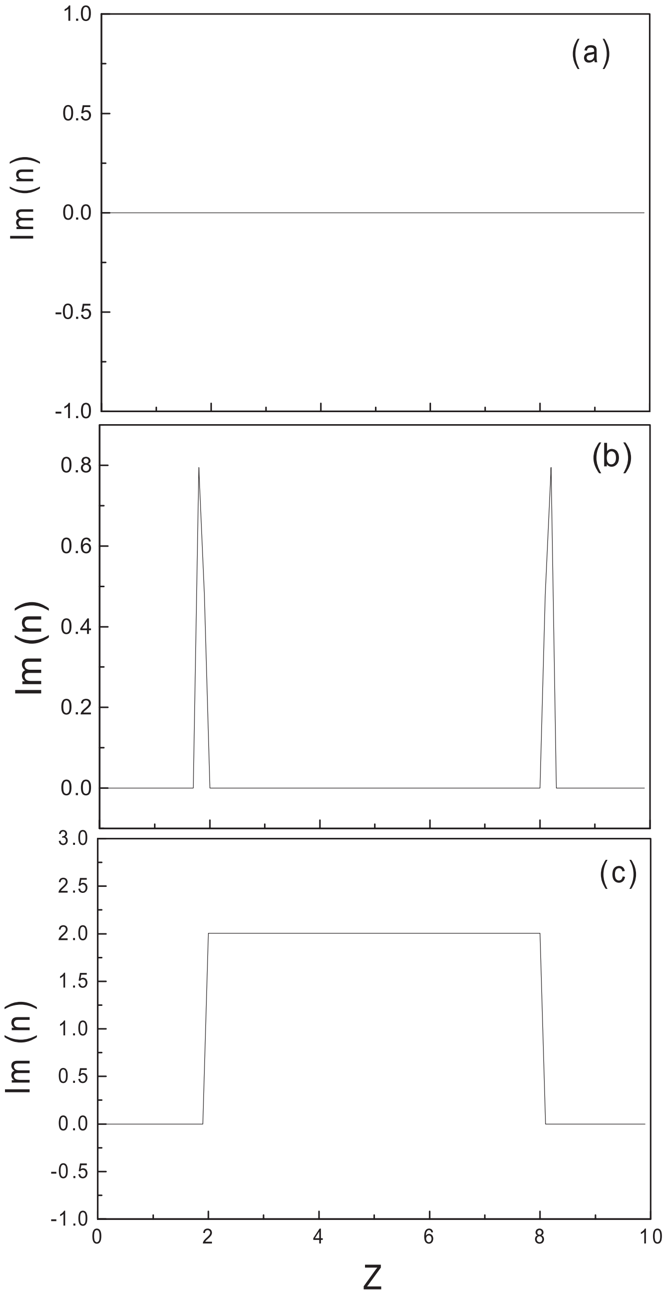

Fig. 5. The imaginary part of the refractive index of probe beam (proportional to the absorption of probe wave) *versus* the distance Z in the non-uniform plasma. The parameters used are $\omega_{p0} = 1.0$, $\omega = 2.25$. (a) $\omega_a = 1.0$, $\Lambda = 0.4$; (b) $\omega_a = 1.25$, $\Lambda = 0.4$; (c) $\omega_a = 1.0$, $\Lambda = 0.6$.

Λ_0 can be found if we let $\omega_a = \omega_{p0}$ into equation (6). In this case, equation (6) becomes:

$$\frac{1}{2}\Lambda\omega_{p0} \geq \omega - \omega_{p0} \tag{8}$$

so that

$$\Lambda_0 = 2(\omega - 2\omega_{p0})/\omega_{p0}. \tag{9}$$

In Figure 4, $\Lambda_0 = 0.5$.

To verify the results above, the imaginary part of the refractive index of probe beam *versus* the distance Z in the non-uniform plasma is drawn in Figure 5. As we see from equation (4) that the conditions for cutoff is independent of whether the probe and driving fields propagating in the same or opposite direction. The curves in Figure 5 are drawn for the same propagation direction of probe and driving waves. Figure 5a shows a situation where the parameters are obtained out of the covered portion in Figures 4, 5b and 5c show the situations corresponding to the parameters obtained from the area covered by solid lines and by dotted lines, respectively. It indicates that the solutions of equations (6, 7) which are shown as the covered portion in Figure 4 are the conditions to change the propagation of the probe beam from transparency to cutoff in the case where ω is higher than ω_{p0}.

4 Conclusion

In this paper, We investigate the propagation of an electromagnetic wave in a non-uniform plasma controlled by EIT with the presence of a driving field. The non-uniform model discussed here is a simplification of a glow discharge plasma. The frequency range for the driving field in which the propagation of the probe wave can be changed from transparency to cutoff is obtained. The results show that the range is dependent on the power of the driving field.

The non-uniform model discussed here is a simplification of a glow discharge plasma. In general, the electron density for the discharge plasma is from $10^{15} \sim 10^{26}$ m^{-3}, and therefore the plasma frequency ranges at the order of $10^9 \sim 10^{14}$ Hz. The frequencies of the electromagnetic waves apply at the corresponding orders. The power density of the driving field is equal to the order of $10^4 \sim 10^{14}$ W/cm^2 when the parameter $\Lambda = 0.1$. It is obvious that the large electron density needs much powerful energy to control the propagation of a wave in the plasma by EIT.

The authors gratefully acknowledge the support from the National Natural Science Foundation of China, and the State Education Ministry of China.

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