Pulse compression caused by a spectral hole in an inhomogeneously broadened line of an amplifier

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Received June 13, 1986; accepted August 13, 1986

We show that enhanced compression of short pulses can be obtained by propagating them through a two-level atom medium characterized by an inhomogeneously broadened atomic line with a spectral hole. The area theorem remains valid, and consequently there is a slowing down of the pulse area compared with that observed in the analogous case of an amplifier without any hole. On the other hand, there are relative increases in the pulse time width and its energy content. Among the special cases, an inhomogeneous atomic line with a zero on the carrier frequency resonance produces a stable pulse with a zero area.

INTRODUCTION

Not long after the creation of the laser, it was realized that the production of reproducible and controllable pulses presented advantageous features. At first, the drive for more intense sources led to the use of short pulses. However, their short duration was soon recognized as an ideal feature that allowed experimenters to explore the domain of ultrafast molecular processes.[1] More recently, the need to produce laser plasmas or to avoid damage to the material where propagation takes effect has necessitated the tailoring of the duration of short pulses.[2] One observes that the pulse energy and the pulse area are determinants in the production of the desired pulse.

Short-pulse manufacturing[3] can be performed intracavity and extracavity. To distinguish these processes, we will denominate them as short-pulse production and pulse compression, respectively. Short-pulse production involves the laser itself and has as an ideal limit the bandwidth of the amplifier gain profile. For a typical intense-pulse amplifier (Nd:glass or Nd:YAG), the duration time limit is as small as a few tenths of a picosecond ($6\ \mathrm{cm}^{-1} < \Delta\omega/2\pi c < 200\ \mathrm{cm}^{-1}$). However, in practice such a limit cannot be obtained because the pulse output is a compromise between the amplification process and the various spectral narrowing mechanisms.[4] The efficient use of the amplification profile to produce ultrashort pulses is an active field of research that is based mostly on mode-locking techniques.[5] In most of these techniques, the objective is to make a number of modes oscillate in phase; a pulsed output is obtained with each pulse in the range of picoseconds. This is the case of self-locking intracavity modulation and passive mode locking by the optical Kerr effect (OKE). On the other hand, passive mode locking by an intracavity saturable absorber (one with simultaneous Q switching has given some of the best results) aims at the absorption properties of the saturable absorber. Therefore, the duration of the pulse has, in addition to the width of the gain curve, the lifetime of the excited state of the saturable absorber[5] as a lower limit.

Pulse compression, on the other hand, is obtained through the production of pulse chirping or spectral broadening. Numerous techniques have been used to obtain pulse compression, but few have been used to enhance the compression that occurs naturally during the pulse propagation itself.[6] The most basic techniques are generalizations of the signal-compression radar techniques,[7] in which chirping followed by a delay line causes pulse compression. In most instances, it is common to use nonlinear materials and sophisticated technical designs of growing complexity as we approach near-atomic resonance of high intensity or short-pulse duration,[8] where the theory of pulse propagation is best suited. However, little use has been made of the nonpassive features of the material wherein the propagation takes effect to obtain the desired result.

When the consideration of the high intensity of the pulses is made, nonlinear features are brought into play. If the problem is off resonance, the treatment follows along the lines of the nonlinear Schrödinger equation (NSE).[3] If we are near resonance, the dielectric where resonant propagation takes effect is described by an ensemble of two-level atoms (TLA's), and the coupled Maxwell–Bloch equations (MBE's) are required. In both cases, it is convenient to distinguish between the transient and the steady behavior of the pulse propagation. A well-known transient feature is the growth of a pulse accompanied by pulse compression in a TLA amplifier.[9–11] A steady feature in both cases is the presence of shape-preserving pulses (solitons). Also, an important characteristic of steady pulses is the strict relationship between the amplitude and the duration of the pulse, which has been used in a number of pulse-compression schemes.

A straightforward application of the MBE area theorem of coherent pulse propagation for an absorber was used by Slusher and Gibbs[12] to compress a pulse. They grew the area of the pulse to 3π and then let it decrease to its steady value of 2π by propagation. The result was the successful compression of the pulse; an elegant theoretical proof of the reasoning behind this method, in terms of the spectral moment conservation laws, is given by Michalska-Trautman.[13] Another use of the area theorem is the superposition, during propagation, of a steady pulse and a narrower weak one,[14] a process that results in a narrower steady pulse. The use of short-duration NSE solitons resulted in the creation of the so-called soliton laser, with a pulsed output. In this case,

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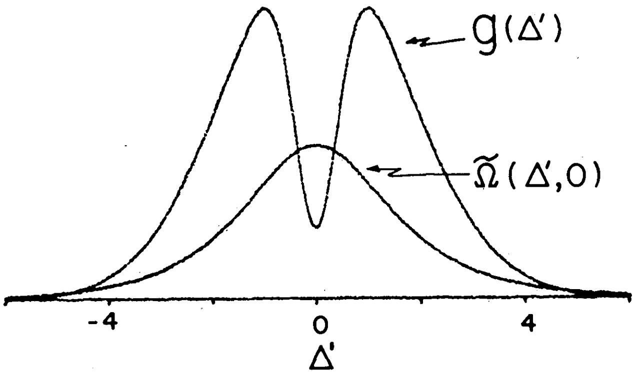

Fig. 1. Spectral distribution $\tilde{\Omega}(\Delta', 0)$ of the incoming pulse at the entrance of the active material. The superimposed curve corresponds to the HB atomic distribution $g(\Delta')$.

the spectral broadening was obtained by propagation in a thin optical fiber, and the compression was obtained by using a delay line.[15]

The use of chirping as a means of getting pulse compression has given a special drive to studying methods of producing chirping. The origin of chirping[16] was explained in terms of dispersion caused by the OKE,[17] the quadratic frequency dependence, and an analogy with microwave theory. All these linear atomic response models predicted chirping in the steady state. However, the presence of chirping in resonant pulse propagation was noticed early.[15] In this case, the atomic linear response assumption must be discarded altogether. A thorough theoretical analysis of OKE stable pulses and the homogeneous atomic broadening was done by Matulic and Eberly,[18] who predicted the occurrence of compressed and chirped optical solitons. Analysis of the inhomogeneous case has been unsuccessful because of the inapplicability of the factorization assumption.[9,10,12] Numerical modeling indicates that pulse compression and chirping will also occur in nonsteady conditions. Experimental confirmation of such predictions and the exploration of their possible use for pulse compression are still pending.

Along different lines of thought, Eberly *et al.*[19] have used selective photoexcitation [hole burning (HB)] of a TLA absorber to obtain the spectral narrowing of a weak pulse. The result is quite the opposite of the one intended here, since the pulse is expanded temporally. This effect suggests the use of an amplifier with a spectral hole, instead of an absorber, to obtain pulse compression, (Fig. 1). The gain profile will behave as an experimentally controllable pulse chirper,[20] with chirping frequencies at the cusps of the atomic line, suitable for enhancing the temporal sharpening of the pulse. For an absorber, the calculation is basically classical, since the medium atomic inversion remains essentially undisturbed. For an amplifier, such an approximation is impossible, and greater care should be taken in handling the problem. However, an attractive reward results when the hole is centered in the TLA resonance. In such a case, we inhibit the on-resonance gain, and, consequently, we slow down the growth of the pulse area. Meanwhile, the off-resonance gain will produce a broader spectral distribution for the pulse. The combined effect seems to constitute an attractive mechanism of pulse compression without the explosive growth typical of amplifiers. This means, on the practical side, that we can compress the pulse and delay the propagation distance in regions where high intensities would become a problem.[21]

In an amplifier, modulation also occurs during the transient propagation, and it is convenient to analyze our method against such a process. If external losses, such as the loss of conductivity, are considered, then the steady behavior reflects the competition between the atomic gain and the external pulse losses. For an atomic line with a spectral hole that inhibits the on-resonance gain, the combined effect of pure loss for the on-resonance component and a combined gain–loss for the off-resonance components will lead to formation of a short null-area pulse, stable and unique.

DYNAMICAL EQUATIONS

The propagating EM pulse is represented by

$$E(z, t') = \mathcal{E}(z, t')\exp(i\omega_c t') + \text{c.c.}, \tag{1}$$

where $t' = t - z/c$ is the local time, c is the speed of light in the medium, and ω_c is the carrier frequency. $\mathcal{E}(z, t')$ is the slowly varying envelope (SVE) of the pulse, in terms of which one defines a more convenient quantity, the complex Rabi frequency

$$\Omega = 2\mu\mathcal{E}/\hbar, \tag{2}$$

where μ is the atomic dipole amplitude. The time evolution of the Rabi frequency is governed by the reduced Maxwell equation

$$\frac{\partial\Omega}{\partial z} = -iBp - \frac{4\pi\sigma}{c}\Omega, \tag{3}$$

where $B = 2\pi N\omega_c\mu^2/\hbar c$, N is the number of atoms per unit of volume, σ is the medium conductivity, and p is the normalized medium polarization. The equations that describe the TLA system for times shorter than the atomic decay times are given by the Bloch equations

$$-i\dot{d} = \Delta d + iw\Omega, \tag{4a}$$

$$\dot{w} = \text{Im}(\Omega d), \tag{4b}$$

where $\dot{d}$ and $\dot{w}$ stand for the local time derivates of the SVE of the atomic dipole d and the atomic inversion w, respectively, of the TLA system, which is characterized by the atomic frequency ω_a and the detuning $\Delta = \omega_a - \omega_c$. The medium is described by a TLA ensemble characterized by the inhomogeneous atomic line $g(\Delta)$. In this case the normalized SVE medium polarization is given by

$$p = \langle d\rangle = \int_{-\infty}^{\infty} dg(\Delta)d\Delta. \tag{5}$$

At a propagation distance z, and after the passing of the pulse has been completed, we can give a local-frequency-dependent representation of the field, i.e., the Rabi frequency $\tilde{\Omega}(\Delta', z)$, and of the SVE polarization $\tilde{P}(\Delta', z)$ by taking the Fourier transform of Eqs. (2) and (4) at a given z. In these terms we can define the local response function $\chi(\Delta', z)$ by

$$\tilde{P}(\Delta', z) = \chi(\Delta', z)\tilde{\Omega}(\Delta', z), \tag{6}$$

where the Fourier variable is $\Delta' = \omega - \omega_c$. On the other hand, from Eqs. (4)–(6), and by using the symbolic relation

$$\lim_{\epsilon\to 0}\frac{1}{\Delta' + i\epsilon} = \mathbf{P}\frac{1}{\Delta'} - i\pi\delta(\Delta'),$$

where P is the principal value, we can obtain an expression for the local response function, which explicitly shows the atomic inhomogeneous line,

$$\chi(\Delta', z) = \chi'(\Delta', z) + i\chi''(\Delta', z), \tag{7a}$$

where

$$\chi'(\Delta', z) = \frac{B}{\tilde{\Omega}(\Delta', z)} \mathsf{P} \left\langle \frac{f(\Delta', \Delta, z)}{\Delta' - \Delta} \right\rangle \tag{7b}$$

and

$$\chi''(\Delta', z) = \frac{B}{\tilde{\Omega}(\Delta', z)} f(\Delta', \Delta', z) g(\Delta'). \tag{7c}$$

We have used the notation

$$f(\Delta', \Delta, z) = F(\Omega w), \tag{7d}$$

where the symbol F stands for the Fourier transform of the product of the atomic inversion and the Rabi frequency as a function of time at a fixed z. Therefore, in general terms, to obtain f we must still solve Eqs. (3) and (4a). Equation (4b) leads to an integrodifferential equation that is not suitable for a similar response function analysis. However, we notice that $\chi''(\Delta', z)$ shows a factorization between $f(\Delta', \Delta', z)$ and $g(\Delta')$, and this is the leading term in defining the atomic loss or gain profile, which shall be defined as the imaginary part of Eq. (7a). Then, despite not knowing the function f explicitly, we can modify the gain profile by modifying the atomic line itself and thus chirping the pulse.

The field propagation equation, given by the reduced Maxwell Eq. (3), can be rewritten as a function of frequency by using Eqs. (6) and (7):

$$\left(\frac{4\pi\sigma}{c} + \frac{\partial}{\partial z}\right)\tilde{\Omega}(\Delta', z) = i\chi(\Delta', z)\tilde{\Omega}(\Delta', z). \tag{8}$$

For each frequency, the left-hand side of this equation indicates an exponential decay with a coefficient given by the pulse external losses, whereas the right-hand side shows the gain and dispersion caused by the excited atoms. The combined competition between these two contributions will lead to the overall output. This process can be expressed in terms of the total integrated energy

$$e(z) = \int [\Omega(t', z)]^2 \,\mathrm{d}t' \tag{9a}$$

$$= \frac{1}{2\pi} \int [\tilde{\Omega}(\Delta', z)]^2 \mathrm{d}\Delta' \tag{9b}$$

and the intensity as a function of frequency

$$I(\Delta', z) = [\tilde{\Omega}(\Delta', z)]^2. \tag{10}$$

From Eq. (8), we can derive the propagation equation that governs $I(\Delta', z)$:

$$\left(\frac{4\pi\sigma}{c} + \frac{\partial}{\partial z}\right)I(\Delta', z) = -2\chi''(\Delta', z)I(\Delta', z). \tag{11}$$

Another important parameter in pulse propagation is the area of the pulse $A(t, z)$ at a point z and up to a time t. The propagation of the total area of the pulse is given by Eq. (8) on resonance. To obtain $\chi(0, z)$, we use the on-resonance solutions of Eqs. (4) to obtain

$$w(t', z, 0) = w_0 \cos A(t, z), \tag{12}$$

where $A(t, z)$ is the pulse area elapsed up to a time t and the propagation distance z, and w_0 is the atomic inversion initial condition. In the long-time limit, $A(t, z)$ will coincide with $\tilde{\Omega}(0, z)$, and $\chi(0, z)$ is given by

$$\chi(0, z) = \left[\frac{\alpha w_0}{2}\right]\left[\frac{\sin \tilde{\Omega}(0, z)}{\tilde{\Omega}(0, z)}\right]. \tag{13}$$

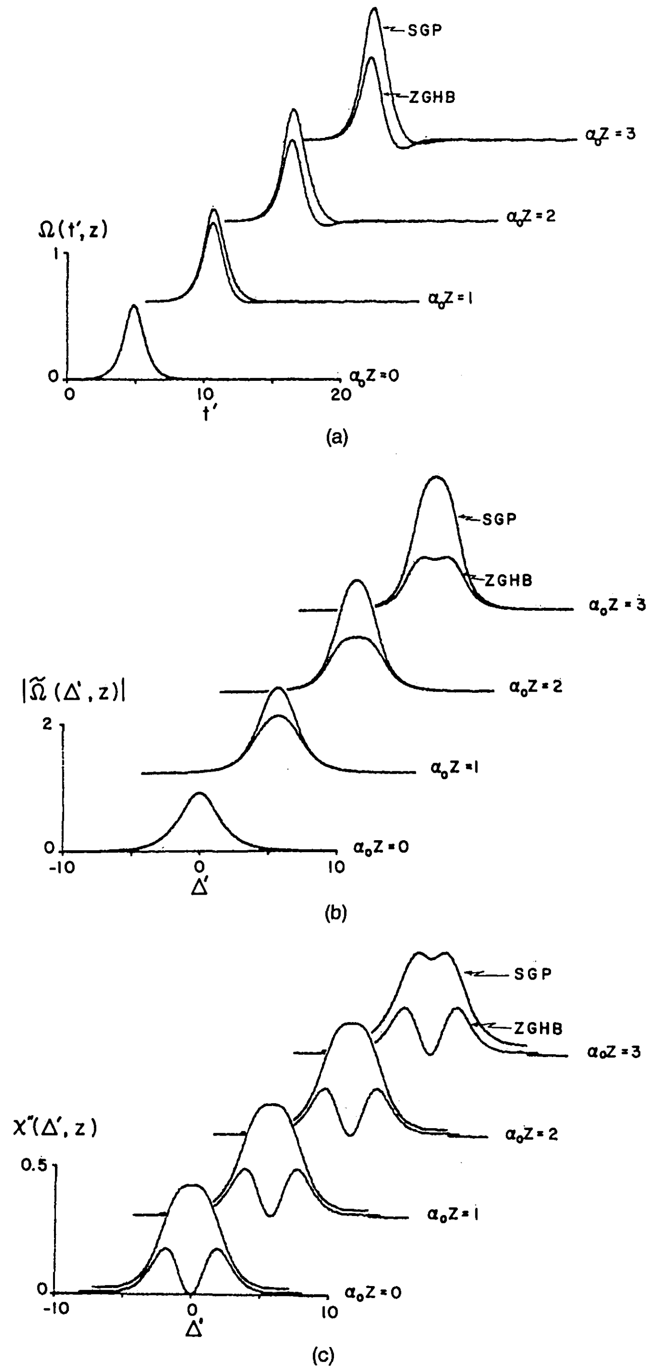

Fig. 2. A weak pulse is propagated in the HB TLA medium. We display (a) $\Omega(t', z)$, (b) $|\tilde{\Omega}(\Delta', z)|$, and (c) $\chi''(\Delta', z)$ in the ZGHB and the SGP cases, the last one in the background. The compression caused by the spectral hole can be noticed in (a). In (b), the modulation that originates the compression is clearly distinguished, as a function of z, in $|\tilde{\Omega}(\Delta', z)|$. The atomic gain profile is shown in (c). The pulse area ZGHB null gain caused by the atomic line hole becomes evident. Notice the hole burn cusps that give rise to the modulation.

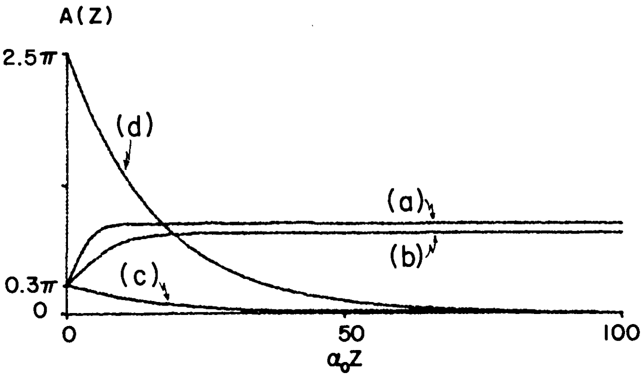

Fig. 3. The area of a pulse during propagation. We show a small-initial-area pulse ($A_0 = 0.3\pi$) propagating in (a) SGP, (b) HSH, and (c) ZGHB amplifiers. A large initial area pulse ($A_0 = 2.5\pi$) propagating in a ZGHB amplifier is shown in (d). If the spectral hole is such that $g(0)$ is finite and such that the atomic gain overcomes the external losses, the pulse area exhibits the behavior predicted by the area theorem at the modified atomic gain rate, (a) and (b). The steady value of the area increases as the depth of the spectral hole decreases. The curves (c) and (d) show large- and small-area pulses in a ZGHB amplifier. Both cases show the exponential decay of the external loss, irrespective of its initial value.

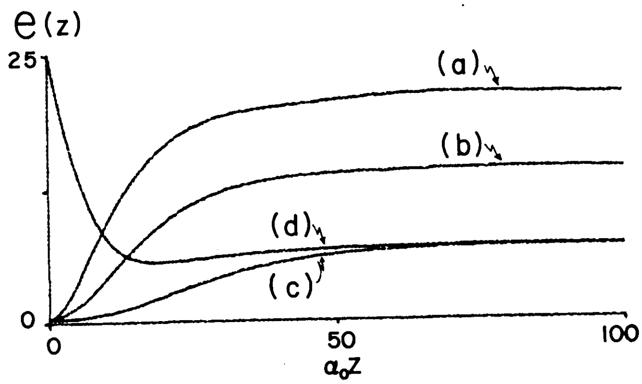

Fig. 4. Energy of the pulse during the propagation. The curves shown in this figure correspond to the cases of Fig. 3. If the initial pulse is weak, it will grow to a steady-state value, (a)–(c). A large initial-area ZGHB case is drawn in (d). Notice the same energy steady value for the ZGHB amplifier, (c) and (d).

The substitution of Eq. (13) into Eq. (8) will result in a variation of the area theorem, where $\alpha = 2\pi Bg(0)$ is the Beer coefficient. If the hole burning is on resonance, it will modify the rate of change of the pulse area. Therefore, if the spectral hole is such that $g(0) = 0$, then the atomic gain or loss of the area is prevented altogether. The steady-pulse area satisfies the relation

$$\tilde{\Omega}_s(0) = \frac{\alpha c w_0}{8\pi\sigma} \sin \tilde{\Omega}_s(0) \tag{14}$$

obtained from Eqs. (8) and (13). The effect on the resonant intensity is analogous [Eq. (11)], but that is not the case for the pulse energy. These combined mechanisms are the basis of this pulse compression technique.

A qualitative measure of the pulse compression is obtained by observing the behavior of the peak amplitude amplification, which is measured as the ratio of the squared area to the pulse energy

$$r(z) = \frac{[\tilde{\Omega}(0, z)]^2}{e(z)}. \tag{15}$$

The increase (decrease) of this parameter is interpreted as the compression (lengthening) of the pulse. A quantitative measurement of pulse compression is given by the second spectral moment,[13]

$$\Delta_\omega^{\,2}(z) = \int \mathrm{d}\Delta'\Delta'^2 I(\Delta', z)/e(z). \tag{16}$$

In the classical limit that occurs in an absorber and a weak field ($w_0 = -1$), Eqs. (7b) and (7c) are real. They are identified with the dispersive and the absorptive parts of the dipole reaction field. In this case $f(\Delta', \Delta, z)$ is just the Fourier transform of the Rabi frequency, which will cancel out from Eqs. (7), leading to well-known expressions for these quantities.[9,10] The effect of a hole in the inhomogeneous atomic line, from Eqs. (7), will modify accordingly the absorptive contribution, slowing down the rate of absorption of the pulse area. In this limit of HB such that $g(0) = 0$ (ZGHB), the on-resonance absorption is inhibited. If the atomic broadening is large enough and the spectral hole is narrow, results will include the spectral pulse narrowing predicted by Eberly *et al.*[19] and an increase in the pulse duration. However, if the atomic broadening is comparable with the pulse spectral width, it will cause pulse oscillations

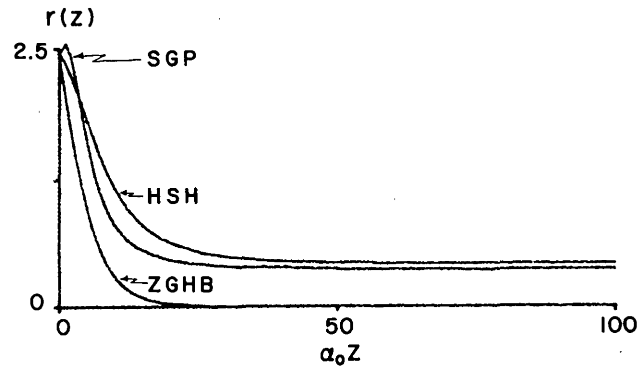

Fig. 5. The parameter $r = A^2(z)/e(z)$, for the weak pulse shown in Figs. 3 and 4, is drawn for the SGP, HSH, and ZGHB amplifiers. Notice the faster transient growth of the area compared with the pulse energy in a SGP amplifier. The steady decay is due to the long-distance stabilization of the area of the pulse while its energy still increases (Figs. 3 and 4). This process results in the compression of the pulse by the amplifier.

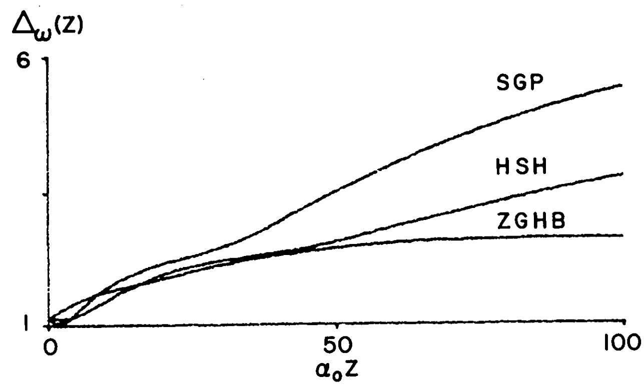

Fig. 6. The spectral width of the pulse Δ_ω is defined in terms of the second spectral moment $\Delta_\omega^{\,2}$ [Eq. (17)]. The curves correspond to the cases presented in Fig. 3. The transient behavior of Δ_ω is to become larger as the depth of the spectral hole increases. The long-distance behavior is the opposite. This explains the pulse compression as a transient phenomenon and the longer 0π duration in comparison with that of the SGP soliton.

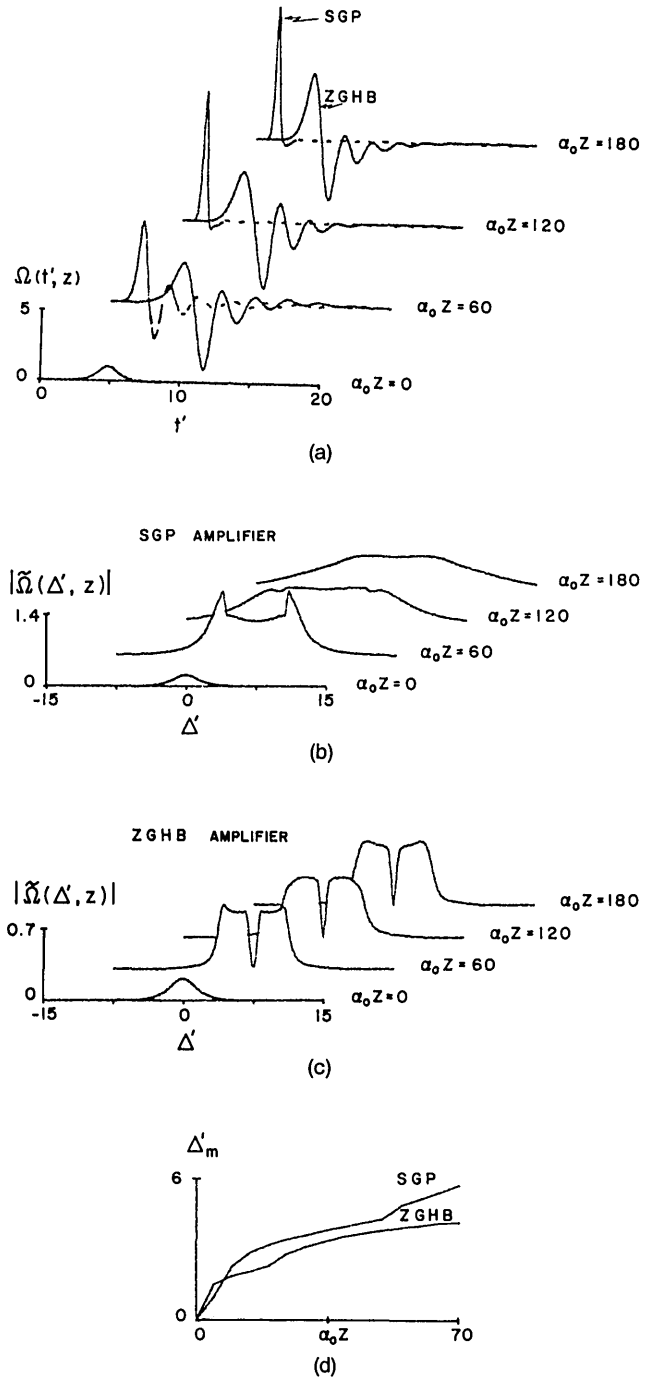

Fig. 7. Long-distance behavior of the propagating pulse in the SGP and ZGHB amplifiers. The SGP amplifier modulation gives place to the generation of a steady pulse of nonzero area A_S, whereas a ZGHB amplifier has one with null area. The modulus of the spectrum of the pulse in both cases is drawn in (b) and (c). The SGP case shows a wide spectral broadening, but the amplification self-modulation is negligible. In the ZGHB case, the spectral broadening is limited, with a hole due to the null area. A numerical determination of the chirping frequencies Δ'_m is given in (d). Δ'_m is determined as the frequencies where the maxima of $|\tilde{\Omega}(\Delta', z)|$ occurs. The symmetry of the spectra has been used to show only the curve for positive frequencies. Modulation is slow to start in a SGP amplifier, but thereafter it will grow to a vigorous pace. In the ZGHB amplifier, early modulation is strong and will quickly reach a near-steady value, surpassed by the SGP value at longer distances. The unequal changes of slope are due to changes in the form of $\tilde{\Omega}(\Delta', z)$. The SGP modulation is transient and will eventually disappear. Note the difference in the scales in (b) and (c).

similar to those caused by anomalous absorption but for a nonzero-area pulse. On the dispersive part, the influence is subtler, since a frequency averaging will be carried out.

In the case of an amplifier without such a spectral hole [one with a standard gain profile (SGP)], there is no analog for the approximation used for the absorber. SGP propagation is characterized by an initial monotonic growth, when the field is small, soon to be accompanied by a simultaneous modulation and compression of the pulse.[9,10,20] The final stage, which corresponds to a stable pulse of definite area, is known from numerical evidence in the general case.[9,10] This behavior is discussed in the following section and is shown in the backgrounds of Figs. 2–7, with which we will make the comparison for the case of a spectral hole in the inhomogeneous atomic line.

PROPAGATION IN AN AMPLIFIER WITH A SPECTRAL HOLE

The aim of this section is to show the pulse compression by hole burning in the gain profile, its range of validity, and the efficiency of the method compared with the one in a holeless (SGP) amplifier. Against this we will compare two cases of amplifiers with a spectral hole (HB): one (ZGHB) with a spectral hole that makes the gain profile null on resonance and another one (HSH) that has a spectral hole that is half the on-resonance amplitude of the SGP. We will compare the transient behavior, the area, the energy, the duration, and the modulation of the pulse in each case. We will conclude with a discussion of the steady pulse of such amplifiers. The relevant results are obtained by numerically integrating Eqs. (3) and (4) and by using fast-Fourier-transform subroutines to obtain Eq. (6). The results are given in a graphical sequence, in which the propagation distance z has been measured in the SGP Beer length α_0.

The spectral hole in the inhomogeneous atomic line shape spoils the on-resonance contribution from the TLA medium and creates two maxima cusps on the gain profile. They will behave as chirping frequencies and cause an early pulse modulation. Their dependence on the propagation distance is small,[20] and their permanence depends on the relative spectral hole width. Such chirping will be eventually overcome by the natural amplification modulation, where this technique will lose its efficiency. The pulse area will be critically affected, slowing down its growth, and the numerical evidence indicates that it is unable to reach stability in large areas if external losses are absent.[9,10] If they are present, they will compete with the on-resonance gain. When this is inhibited by a ZGHB gain, the pulse area decay will set and will result in a stable zero-area pulse [Eq. (14)]. If the spectral hole has a finite depth, the problem is analogous to that of the SGP amplifier, and the numerical evidence shows that a steady pulse is of the SGP soliton type. The values of the steady-pulse energy e_S and area A_S get smaller as $g(0)$ does, i.e., as the spectral hole becomes deeper. In the ZGHB amplifier limit, A_S must be null [Eqs. (14)], and e_S must be unique for any value of the initial area. From this and from numerical evidence, the uniqueness of the 0π pulse is concluded.

The transient behavior of ZGHB and SGP amplifiers is shown in Fig. 2. The comparison between the two pulses is established in their temporal display and their spectrum and atomic gain [Eq. (7c)]. In this regime, the pulse compression is clearly noticeable, and it is due to the different effects of the two amplifiers on the pulse. The SGP amplifier essentially amplifies the pulse, whereas the ZGHB amplifier broadens spectrally, modulates, and holds down the area of the pulse. In the spectrum, we can see the two cusps that will spectrally broaden and modulate the pulse in the ZGHB amplifier. This modulation is not the one that will occur later in an SGP amplifier.

The area and the energy of the pulse are shown in Figs. 3 and 4, respectively. If the consideration of a external loss (conductivity) is made, then the area in a ZGHB amplifier has an exponential decay at the loss rate of the decay. On the other hand, for a HSH amplifier, atomic gain will set until a balance is reached between the atomic gain and the external loss. The behavior of the energy [Eq. (9)] follows the more traditional pattern for an amplifier and has a monotonic growth until it reaches a nonzero limiting value e_S, which decreases as the depth of the spectral hole increases.

The study of the pulse duration as a function of the propagation distance can be given by the ratio $r(z)$, which relates the area and the energy of the pulse with the spectral second moment $\Delta_\omega{}^2$. Both of them are defined in Eqs. (15) and (16), and they are displayed in Figs. 5 and 6, respectively. The curves correspond to SGP, HSH, and ZGHB amplifiers for each of the figures. If the net effects of a spectral hole on the area are losses, the parameter $r(z)$ is monotonically decreasing toward its steady value. In the SGP case, there is a transient growth before it also settles into a monotonic decreasing behavior, when the area gain is null. A quantitative measurement of the pulse duration is given by the spectral width of the pulse Δ_ω. This will increase if there is a spectral hole, and it is monotonically increasing up to a steady value in the case of a ZGBH amplifier. In a SGP amplifier, it will exhibit a transitory decrease before it grows to a value that is the greatest of the steady values for HB amplifiers.

These results can be interpreted as an early amplification and a poor increase of the energy content of the pulse for a SGP amplifier, whereas in a HB amplifier the process is the opposite. This transient behavior will hold until the pulse tends to stabilize in a SGP amplifier, at which point this process will be reversed. Furthermore, the steady pulse in each amplifier will fix the value of such a limiting value for Δ_ω. In conclusion, the pulse-compression effect in a HB amplifier is a transient effect that increases its effectiveness as the depth of the spectral hole increases.

The long-distance pulse propagation study will provide the clues at this reversal of the pulse compression. In a SGP amplifier, the initial amplification gives way to pulse modulation and thereafter to an unchirped steady pulse of finite area. On the other hand, a ZGHB amplifier avoids the amplification stage and produces a 0π pulse. In Fig. 7 we show the temporal display of the pulse for both amplifiers, their spectra, and the frequencies at which each spectrum reaches a maximum. These frequencies tell us about the modulation frequencies acting on the pulse. Such modulation was noticed early for a ZGHB amplifier. It persists and is the origin of the 0π steady pulse. In the case of a SGP amplifier, the modulation is a transient effect that does not occur at early times but is far more pronounced than in the case mentioned before [Fig. 7(c)]. However, in this nearly steady domain, the SGP broadening of the range of frequencies where amplification occurs is poor. In a SGP amplifier, the steady-pulse process is more efficient and results in a SGP steady pulse shorter than the ZGHB steady pulse or any other HB steady pulse.

At this point we should stress that for an amplifier the distance at which steady pulse occurs is quite large[9,10] and that, although pulse compression is a transient mechanism, it will hold for the typical experimental propagation distances. At very long distances, in the steady regime, the 0π pulse generated for a ZGHB amplifier is one with large partial areas. Therefore it is a pulse that is not generated by

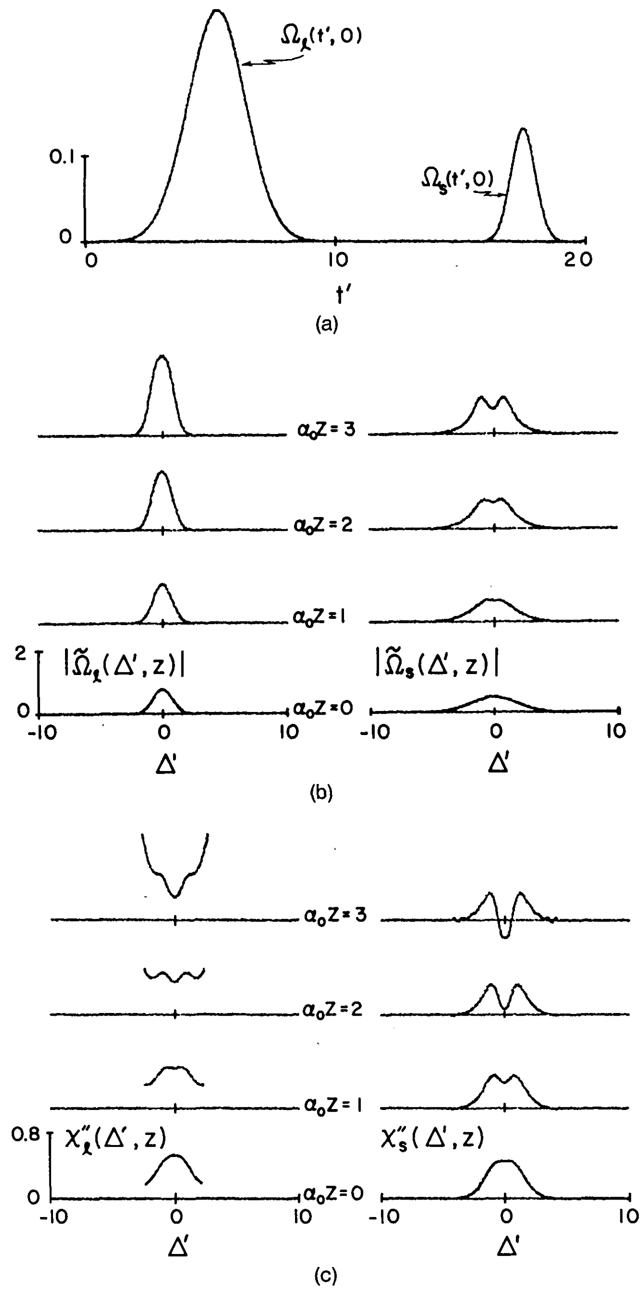

Fig. 8. HB by propagation. (a) A not very weak long pulse $\Omega_l(t', z)$ running ahead of a short pulse $\Omega_s(t', z)$ creates a hole burn on the atomic gain profile. (b) The pulse spectrum shows amplification for the long pulse and shows modulation and an inhibited area growth for the short one. (c) The gain profile for each one shows only gain for the long pulse and a mixed gain–loss for the short one.

anomalous absorption[23] or a superposition of solitons, is not a modulated one, and has not been theoretically predicted until now.[24]

The spoiling of the absorption coefficient α, caused by the spectral hole, will have an effect on other features associated with pulse propagation in amplifiers, such as superradiance, amplifier damage, and self-focusing. The relation between superradiance and propagation is expressed by the Friedberg–Hartmann relation[10]

$$\alpha L = \frac{2\pi g(0)}{\tau_N}, \tag{17}$$

where L is the length of the amplifier bar and τ_N is the superradiant decay rate. When αL is small, absorption is negligible, and superradiance will not occur. A measurement of the tendency of the beam to break up the amplifier rod is given by the **B** integral defined by[25]

$$\mathbf{B} = \frac{2\pi\gamma}{\lambda}\int I\mathrm{d}z, \tag{18}$$

and that limits the diameter d_a of the rod. In this case, $\gamma = 4\pi \times 10^{-7}\ (\eta_2/\eta_0 c)$, where η_2 is the nonlinear refractive index. If the amplification were exponential, it will be governed by Eq. (13), which through the atomic inversion is proportional to the amplifier pumping; therefore B is proportional to d_a. However, Eq. (13) is also proportional to $g(0)$, and because of the spectral hole this reduces or removes the dependence on d_a, making B smaller. On the other hand, phase modulation and propagation transversal effects are associated with nonlinearities.[16] A transversal effect of special importance is the coherent on-resonance self-focusing, which has different features than its off-resonance analog[21] that occurs for $5 < \alpha L < 30$.[26] Because of the spectral hole, we reduce its effect or avoid it by spoiling the amplification. A numerical analysis of this problem and its comparison with methods in which a defocuser medium is introduced in order to avoid self-focusing[27] will be presented in a future publication.

Finally, we discuss a procedure to generate a spectral hole during propagation. This consists of running a long pulse ahead of the short pulse to be compressed. In Fig. 8(a) we exhibit the temporal display of the pulses. In Figs. 8(b) and 8(c) we show their spectra and their atomic gain for four propagation distances within the TLA amplifier. We can observe that the first (long) pulse tends to be exponentially amplified by the medium. This amplification causes a depletion in the population inversion of the near-resonant atoms, and the second (short) pulse sees an amplificating medium with an inhibited near-resonant gain, i.e., with a spectral gain profile with a hole. The long pulse cannot be arbitrarily weak if it is expected to be efficient in burning the spectral hole. This can be easily explained in terms of the area theorem, which states that for very weak or large pulses the gain is poor. Experimental evidence of this effect has been observed.[27]

CONCLUSIONS

Pulse compression by an inhomogeneous hole burning is a transient coherent-pulse-propagation phenomenon. Its range of applicability is well within the domain of experimental feasibility. The spectral hole in the inhomogeneous broad line inhibits the growth of the area of a pulse propagating in an amplifier. On the other hand, the hole will cause reshaping of the spectral distribution of the pulse, which will become spectrally broader and temporally shorter. This process is caused by the spectral hole modulation, which will eventually be overcome by the inhomogeneous medium pulse-amplification self-modulation $A_S \neq 0$. The validity of these regimes is directly associated with the width of the spectral hole, but the distinction is not obvious, since there is not a unique connection between the spectral hole and the dispersive and absorptive response functions. In the HB case with $A_S = 0$, those frequencies persist and give origin to the 0π pulse.

Spectral holes of smaller amplitudes are more appropriate than those in the ZGHB case for use in comparisons with standard pulse-compression techniques. To compare this method and the ones based on chirping by nonlinear materials, it is necessary to consider the ease of creating the required spectral hole against the availability of appropriate nonlinear materials. In this case, high intensity and near resonance are extremely restrictive on the availability of the suitable material. The independence of the method from nonlinear materials but not from the amplifier itself lends it a greater transportability and experimental control. This method also suggests an alternative explanation for the self-chirped output in mode-locked lasers[21] or its use as a first stage of pulse compression by a grating pair. However, if the minimum of the spectral hole is null or negative, as is the case when the inversion is negative near the resonant frequencies, it will strongly reinforce the features observed due to the competition of amplification off resonance and absorption near resonance for the ZGHB amplifier.

The ZGHB steady pulse is quite interesting by itself. It is a 0π pulse of large partial areas. Because of its large partial areas and its zero total area, it is suitable to become a steady 0π pulse in an absorber, without the typical problems of stability or anomalous absorption.

ACKNOWLEDGMENTS

J. J. Sanchez-Mondragon would like to thank J. H. Eberly for enlightening discussions and the support to carry on a long-standing collaboration. Special thanks are due to B. Griffin for her hospitality. This work was partially supported by the Consejo Nacional de Ciencia y Tecnologia. J. J. Sanchez-Mondragon was commissioned by Centro de Instrumentos, Universidad Nacional Autonoma de Mexico.

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