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Novel self-mode-locking mechanism in narrow-band lasers

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We suggest a novel self-mode-locking (SML) mechanism in narrow-band lasers. The analysis for such a mechanism show that the gain-line splitting (Stark splitting) induced by an intracavity laser field can form a dip or dips in gain-line shape, and the gain medium with such a gain-line shape can produce short pulses. The further analyses give the rough criterion for SML, i.e., $8\ln(2)\Delta\omega_s^2>\Delta\omega_g^2$ for the gas lasers and $12\Delta\omega_s^2>\Delta\omega_g^2$ for the solid or liquid lasers.

Mode locking without any additional passive or active elements (but gain medium) to be introduced in laser cavity in order to produce short pulses is named as self-mode-locking (SML). The SML phenomenon was first observed in a He-Ne laser,[1] its SML mechanism was first analyzed in Lamb's theory,[1,2] but the cause of phase locking has not been understood clearly. In the study of SML in copper vapor lasers, the cause was first thought as nonuniformity of the active zone,[3] but the further experimental results disagreed with this view.[4] Recently, in the experiments of CuBr lasers, highly stable SML pulses have been obtained by using an aperture to control transverse modes,[5] but the cause has not been known. Moreover, since CuBr vapor is not a self-focusing medium, it cannot be explained by the Kerr self-focusing model in SML solid-state lasers.[6]

In this letter, we concentrate our studies only on the SML mechanism in narrow-band lasers and suggest a novel SML mechanism, which depends on the Stark splitting of active medium induced by intracavity laser field. In order to make out this mechanism, we first analyze the deformation of an amplified pulse which mainly depends on the gain-line shape and gain saturation. Usually, the gain-line shape is regarded as Lorentzian or Gaussian profile which corresponds to homogeneous or inhomogeneous broadening laser medium.[7,8] Both line shapes are convex upwards, and the gain at the frequency center is larger than that at wings. If the frequency center of pulses is equal to frequency center of gain, the pulses through this laser medium are broadened. The gain saturation also makes the pulses broadened. SML does not occur in these lasers. But if the intracavity laser field is strong enough, there will be a dip or dips in the gain-line shape due to the Stark splitting. The gain medium with such a gain-line shape will produce short pulses,[9] and SML is allowed. Since the Stark splitting is symmetric, there is no additional group-velocity dispersion (GVD). The SML pulses without dispersion compensation will occur in those lasers whose gain media have a dip in the gain-line shape, if the nonlinearity and GVD of the host materials can be neglected.

For gas lasers, if the influence of their host materials can be neglected, all actions stem from excited atoms in these laser media. The gain coefficient can be written as (inhomogeneous broadening)[7]

$$g(\omega,I)=g(\omega)/\sqrt{1+I/I_s}, \tag{1}$$

where I_s is the modified saturation intensity of the gain medium. For ultrashort pulses, if pulses through the laser medium obtain little energy on a single pass, I_s can be expressed approximately as follows:

$$I_s=\frac{E_s}{\tau_{\text{ext}}}\left(1+\frac{L}{c\tau_p}\right), \tag{2}$$

where E_s is the saturation energy, τ_{ext} the lifetime of the excited state, τ_p the pulse width, and L the cavity length. Assuming that the small-signal gain $g(\omega)$ has a Gaussian line shape with respect to the frequency ω, it can be written as

$$g(\omega)=g(\omega_0)\exp-\left[4\ln(2)\left(\frac{\omega-\omega_0}{\Delta\omega_g}\right)^2\right], \tag{3}$$

where ω_0 is the central frequency and $\Delta\omega_g$ is full width at half-maximum of the laser gain-line shape.

For simplicity, suppose that the frequency shift of the Stark splitting induced by the laser field is $\Delta\omega_s$ from the unperturbed frequency, therefore

$$g(\omega)=\frac{1}{2}g(\omega_0)\left\{\exp-\left[4\ln(2)\left(\frac{\omega-\omega_0+\Delta\omega_s}{\Delta\omega_g}\right)^2\right]\right.$$
$$\left.+\exp-\left[4\ln(2)\left(\frac{\omega-\omega_0-\Delta\omega_s}{\Delta\omega_g}\right)^2\right]\right\}. \tag{4}$$

In the case of $4\ln(2)(\omega-\omega_0)^2<\Delta\omega_g^2$ or $\Delta\omega_g^4/[4\ln(2)\Delta\omega_s^2]$, Eq. (4) can be expanded into series about $\omega=\omega_0$,

$$g(\omega)\cong g(\omega_0)\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right]$$
$$\times\left(1+\frac{4\ln(2)[8\ln(2)\Delta\omega_s^2-\Delta\omega_g^2]}{\Delta\omega_g^4}(\omega-\omega_0)^2\right). \tag{5}$$

If $I<I_s$, Eq. (1) can be expected into

$$g(\omega,I)\cong g(\omega_0)\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right]\left(1-\frac{I}{2I_s}+\frac{4\ln(2)[8\ln(2)\Delta\omega_s^2-\Delta\omega_g^2]}{\Delta\omega_g^4}(\omega-\omega_0)^2\right). \tag{6}$$

If the laser output is regarded as a part of linear absorption, the place of 1 is taken by α in the bracket of Eq. (6) ($1-\alpha$ is proportional to absorption coefficient). According to the theory of light interacting with matter, the change of the refractive index $\Delta n(\omega,I)$ and the changes of the wave number differential $\Delta K'(\omega_0,0)$ and $\Delta K''(\omega_0,0)$ can be obtained by first-order approximations:

$$\Delta n(\omega,I)\cong\frac{2\sqrt{\ln(2)}n(\omega_0)g(\omega_0)(\omega-\omega_0)}{\omega\Delta\omega_g}\times\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right], \tag{7}$$

$$\Delta K'(\omega_0,0)=\frac{2\sqrt{\ln(2)}n(\omega_0)g(\omega_0)}{\Delta\omega_g}\times\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right], \tag{8}$$

$$\Delta K''(\omega,0)=0, \tag{9}$$

where c is the light velocity in vacuum; $n(\omega_0)$ the refractive index at $\omega=\omega_0$, $\Delta K'(\omega_0,0)$ represents the reciprocal of the additional group velocity; $\Delta K''(\omega_0,0)$ represents the additional group-velocity dispersion (GVD).

Considering the electric field strength of an optical pulse $E(z,t)=\psi(z,t)\exp[i(Kz-\omega t)]$, where $\psi(z,t)$ is the slowly varied pulse envelope, the following can be obtained

$$\frac{\partial\psi}{\partial z}=\frac{1}{2}g(\omega,I)\psi-\Delta K'\frac{\partial\psi}{\partial t} \tag{10}$$

and

$$\frac{\partial\psi}{\partial z}=\frac{1}{2}g(\omega_0)\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right]\left(\alpha-\frac{I}{2I_s}+\frac{4\ln(2)[8\ln(2)\Delta\omega_s^2-\Delta\omega_g^2]}{\Delta\omega_g^4}(\omega-\omega_0)^2\right)\psi-\Delta K'\frac{\partial\psi}{\partial t}. \tag{11}$$

By the correspondence

$$-i(\omega-\omega_0)\leftrightarrow\frac{\partial}{\partial t}\quad\text{and}\quad I\leftrightarrow|\psi|^2 \tag{12}$$

and let

$$\xi=\frac{1}{2}zg(\omega_0)\exp-\left[4\ln(2)\left(\frac{\Delta\omega_s}{\Delta\omega_g}\right)^2\right]\quad\text{and}\quad\tau=t-\Delta K'z, \tag{13}$$

Eq. (11) can be translated into

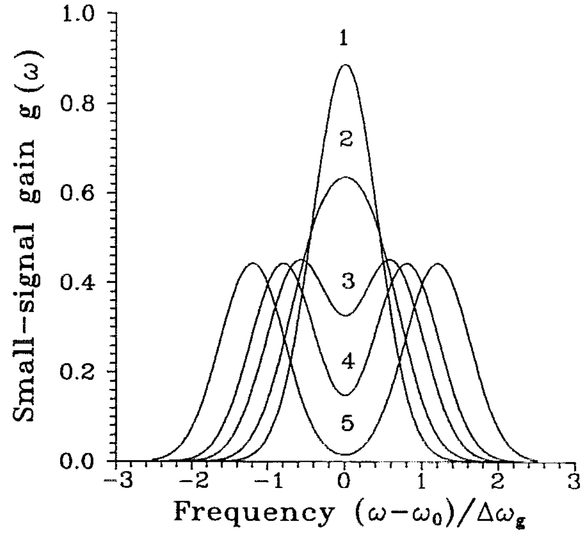

FIG. 1. The small-signal gain line shapes are changed by Stark splitting in a gas narrow-band laser. Curves 1, 2, and 3–5 correspond, respectively: $\Delta\omega_s=0$, $8\ln(2)\Delta\omega_s^2=\Delta_g^2$ and $8\ln(2)\Delta\omega_s^2>\Delta\omega_g^2$.

$$\frac{\partial\psi}{\partial\xi}=\alpha\psi-\frac{1}{-2I_s}|\psi|^2\psi-\frac{4\ln(2)[8\ln(2)\Delta\omega_s^2-\Delta\omega_g^2]}{\Delta\omega_g^4}\frac{\partial^2\psi}{\partial\tau^2}. \tag{14}$$

If $8\ln(2)\Delta\omega_s^2>\Delta\omega_g^2$, Eq. (14) has pulse solution so that the SML pulses can occur in gas lasers. $8\ln(2)\Delta\omega_s^2>\Delta\omega_g^2$ is called the SML criterion. If this criterion is put into Eq. (4), a dip gain-line shape (small-signal gain) will be obtained. But this gain-line shape is disagreed with the spectral shape of output pulses reported in Ref. 10, it is because the spectral shape includes the action of gain saturation, which smears the peaks appeared in small-signal gain-line shape.[11] Several typical gain-line shapes are described in Fig. 1, where curve 1 is the case without the Stark splitting ($\Delta\omega_s=0$); curve 2 the critical case mode locked by Stark splitting [$8\ln(2)\Delta\omega_s^2=\Delta\omega_g^2$]; curves 3–5 the case mode locked by Stark splitting [$8\ln(2)\Delta\omega_s^2>\Delta\omega_g^2$]. In solid or liquid narrow-band lasers, the Lorentzian line shape (homogeneous broadening) should be considered so that the SML criterion is $12\Delta\omega_s^2>\Delta\omega_g^2$. The corresponding gain-line shapes are described in Fig. 2, where curve 1 is the case without Stark splitting ($\Delta\omega_s=0$); curve 2 the critical case mode locked by Stark splitting ($12\Delta\omega_s^2=\Delta\omega_g^2$); curves 3–5 the case mode locked by Stark splitting ($12\Delta\omega_s^2>\Delta\omega_g^2$). For gas lasers, if the nonlinearity and GVD of the host material can be neglected and $\Delta K''=0$, it is unnecessary to compensate for the GVD; if not, it is necessary to compensate for the GVD by an intracavity prism pair. For solid-state or liquid lasers, the nonlinearity and GVD of the host materials play important roles in their SML and it is necessary to compensate for the GVD.

Now we analyze the SML cases in three kinds of lasers (He-Ne, copper vapor and CuBr laser). For the three kinds of lasers, a copper vapor laser not only has the largest power density (about 10^5 W/cm^2), but has the largest gain linewidth $\Delta\omega_g$ (about 10^{10} Hz). $\Delta\omega_s$ in the same order with $\Delta\omega_g$ corresponds to an electric field of about 10^3–10^4

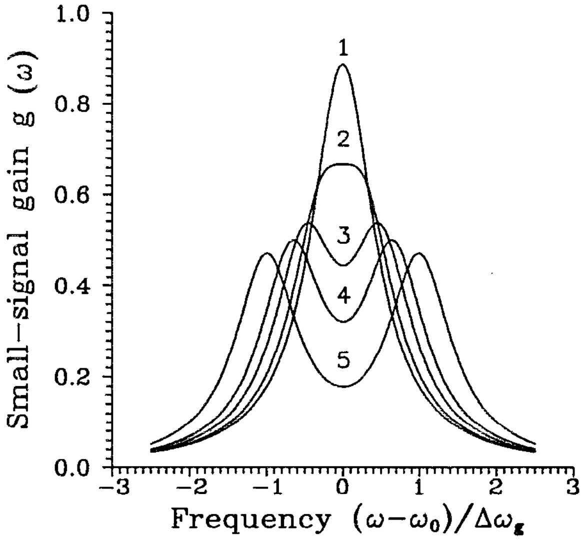

FIG. 2. The small-signal gain line shapes are changed by Stark splitting in a solid or liquid narrow-band laser. Curves 1–5 correspond, respectively: $\Delta\omega_s=0$; $12\Delta\omega_s^2=\Delta\omega_g^2$; $2\Delta\omega_s=\Delta\omega_g$; $3\Delta\omega=2\Delta\omega_g$; $\Delta\omega_s=\Delta\omega_g$.

V/cm [$E\propto(\hbar\Delta\omega_s)/(ea)$, where E is the electric field strength; $\hbar$ is the Planck's constant divided by 2π; e the electric charge of an electron; and a the Bohr radius]. If the electric field is induced by the intracavity laser field. The power density must be about 10^5–10^6 W/cm^2 to satisfy the SML criterion. In fact, it is difficult to reach such a power density by an intracavity laser field. Therefore, the SML is unstable. For a He-Ne laser, its gain linewidth is the narrowest and its power density is the lowest in three kinds of lasers. The analysis shows that its SML is usually unstable again. For a CuBr laser, its linewidth is narrower than a copper vapor laser since its operating temperature is lower, then its SML needs lower power density; although its linewidth is larger than a He-Ne laser, its power density has much larger. Therefore, its SML is the easiest and stablest in the three kinds of lasers.

The above conclusions are obtained under the condition of direct current (dc) electric field. In fact, the laser field is a pulsed alternating electromagnetic field. In a detailed discussion, $\Delta\omega_s$ should be considered as the function of $\psi(z,t)$ (dynamic Stark effect). In addition, the Stark splitting can form a gain-line shape with several dips, which can be analyzed in a similar manner. The width of SML pulses is related to the dip width, which can be tuned by changing the external high-voltage dc electric field. But there are some difficulties in technology to exert a high-voltage electric field on discharged laser tubes. On the other hand, the frequency of the gain-line center can vary with the change of the intracavity laser intensity due to the Stark effect.

In summary, the mode locking of lasers can be thought as two types of balance: The balance between pulse broadening and pulse shortening; the balance between the phase shift by GVD and one by nonlinearity (self-phase modulation). If the former balance is not obtained, the mode-locking pulses will not occur; if only the former balance is obtained, the mode-locking pulses can occur but will be unstable; if both balances are obtained, the stable mode-locking pulse will occur. In the above analysis, the pulse shortening can be obtained by the Stark splitting in narrow-band lasers. It can also be obtained by self-absorption in broadband lasers as illustrated by self-absorption spiking in the gain of Ti: sapphire lasers.[12] This may be the reason why the SML pulses occur in Ti: sapphire lasers. Besides, SML pulses can be obtained by other pulse shortening properties of the laser medium such as the Kerr self-focus effect.[6]

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