MODE LOCKING AND ULTRASHORT LIGHT PULSES IN SMBS IN AN OPTICAL RESONATOR

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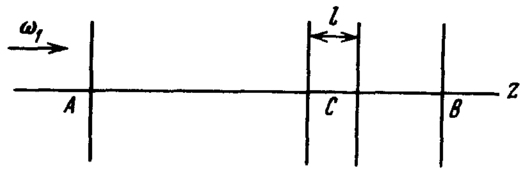
It is shown theoretically that excitation in an optical resonator permits synchronization of the backward SMBS components; this synchronization is brought about by a parametric amplification mechanism and leads to formation of ultrashort light pulses.

The well known method of laser mode locking with the aid of a saturable absorber can be used in principle also to synchronize the components of backward stimulated Mandel'shtam-Brillouin scattering (SMBS) excited in an optical resonator in the stationary regime [1]. In the present communication we indicate the possibility of phasing the components of the SMBS and producing ultrashort light pulses without using a saturable absorber in the resonator.

Let the SMBS be excited in a resonator with flat mirrors located at the points A and B (Fig. 1). The position of the scattering medium in the resonator is determined by the point C. We consider a one-dimensional problem, assuming that the field is independent of the coordinates x and y. The resonator is excited by a linearly polarized plane monochromatic wave whose frequency ω_1 coincides with one of the natural frequencies of the resonator. The frequency difference between the neighboring longitudinal modes, $\Delta\omega_0$, is assumed to be constant in the spectral region of interest to us, which is not too broad. Let the resonator length be such that $\Delta\omega_0 = \Omega/m$, where Ω is the frequency shift of the backward SMBS excited by radiation of frequency ω_1 with the Bragg condition $m = 1, 2\ldots$ satisfied. To obtain intense SMBS we must prevent excitation of anti-Stokes components. We assume therefore that the mirror reflection coefficient for the frequencies $\omega > \omega_1$ is $R \sim 0$. To simplify the analysis, furthermore, we limit the number of Stokes components, putting $R \sim 0$ for $\omega < \omega_n$, where $\omega_n = \omega_1 - (n - 1)\Omega$.



Resonator for SMBS excitation

Let the point C occupy one of the positions satisfying the condition

$$\eta = \frac{\widetilde{CB}}{\widetilde{AB}} = \frac{\kappa}{2m}, \tag{1}$$

where the tilde denotes the optical path length, and $\kappa = 0, 1\ldots 2m$. At $\kappa = 1, 2 \ldots 2m - 1$, the point C determines the center of a scattering medium of length ℓ. At $\kappa = 0$ and $2m$, the scattering medium is located directly at one of the mirrors and has a length $\ell/2$. We consider the simplest case when $\ell \ll \ell_{coh} = \pi u/\Delta\omega$, where ℓ_{coh} is the coherence length corresponding to a spectrum width $\Delta\omega = \omega_1 - \omega_n$ and u is the group velocity of light in the scattering medium.

Under the formulated conditions, the stationary solution for the intensity of the linearly polarized electric field inside the scattering medium can be sought in the form

$$E = \sum_{j=1}^{n} (E_j^+ + E_j^-);\quad E_j^{\pm} = \mathcal{E}_j^{\pm}(z)\, e^{i(\omega_j t \mp k_j z)},$$

where $\omega_j = \omega_1 - (j - 1)\Omega$, $k_j = \omega_j/v_j$, and v_j is the phase velocity of light of frequency ω_j. Let the origin $z = 0$ be located at the point C. The following equations hold then for the $\mathcal{E}_j^{\pm}$

$$\frac{d\mathcal{E}_j^+}{dz} = \frac{\mu c b}{16\pi}\left[\mathcal{E}_{j-1}^-\left(\sum_{\alpha=1}^{n-1} \mathcal{E}_\alpha^{-*}\,\mathcal{E}_{\alpha+1}^+\right) - \mathcal{E}_{j+1}^-\left(\sum_{\alpha=1}^{n-1} \mathcal{E}_\alpha^+\,\mathcal{E}_{\alpha+1}^{-*}\right)\right],$$

$$\frac{d\mathcal{E}_j^-}{dz} = -\frac{\mu c b}{16\pi}\left[\mathcal{E}_{j-1}^+\left(\sum_{\alpha=1}^{n-1} \mathcal{E}_\alpha^{+*}\,\mathcal{E}_{\alpha+1}^-\right) - \mathcal{E}_{j+1}^+\left(\sum_{\alpha=1}^{n-1} \mathcal{E}_\alpha^-\,\mathcal{E}_{\alpha+1}^{+*}\right)\right]. \tag{2}$$

Here μ is the refractive index of the medium, c the speed of light in vacuum, and b is the stationary gain of the backward SMBS. At $\beta = 0$ and $n + 1$ we must put $\mathcal{E}_\beta^{\pm} = 0$. It is assumed that

$\Delta\omega << (\omega/2)(\delta\Omega/\Omega)$, where $\delta\Omega$ is the width of the thermal scattering line. Putting $\mathcal{E}_j^{\pm} = |\mathcal{E}_j^{\pm}|\exp(i\phi_j^{\pm})$, it is easy to show on the basis of (2) with allowance for (1) and for the boundary conditions on the mirrors that the phase shifts $\phi_j^{\pm}$ do not depend on z, and that when j varies from 1 to n - 1 the following phase differences remain constant:

$$\phi_j^+ - \phi_{j+1}^- = \Delta\phi^+ = \text{const}$$
$$\phi_j^- - \phi_{j+1}^+ = \Delta\phi^- = \text{const}. \tag{3}$$

The quantities $\Delta\phi^+$ and $\Delta\phi^-$ are interrelated by the conditions on the mirrors. The phase shift ϕ_1^+ is expressed in terms of the phase shift of the exciting beam. The remaining phase shifts are determined in terms of ϕ_1^+ and an arbitrary constant, which can be chosen to be one of the phase shifts, say ϕ_2^+. The system (2) reduces to equations for the real quantities $|\mathcal{E}_j^{\pm}|$, which can be determined if the modulus of the amplitude of the wave incident on the resonator is given.

From (3) and the boundary conditions on the mirrors it follows that

$$\phi_j^+ - \phi_{j+1}^+ = \Delta\phi^+ - 2\pi\eta q_{j+1} - \pi,$$
$$\phi_j - \phi_{j+1}^- = \Delta\phi^- + 2\pi\eta q_{j+1} + \pi, \tag{4}$$

where q_{j+1} is the number of half-waves spanned by the resonator length for the (j + 1)-st component. It is seen from (4) and (1) that for even κ all the SMBS components are synchronized, whereas for odd κ every other component is synchronized. In the former case the ultrashort light pulses follow each other at time intervals $2\pi/\Omega$, and in the latter cases the pulses have exactly the same duration and the intervals between them are π/Ω.

We supplement the foregoing simple analysis with a number of conclusions that follow from a more detailed consideration. It turns out that under the conditions described above the SMBS components can be synchronized also if $\ell \sim \ell_{coh}$. If the artificial limitation on the number of Stokes components is lifted, the number of these components, which are excited with a progressively decresasing intensity, can be characterized by an "effective" value n_{eff} that depends on ℓ, on the energy input to the resonator, and on the losses in the resonator. The spatial extent of the ultrashort pulses is determined by the length of the scattering medium.

The "energy benefits" ensuing from the phasing of the components is due to the effective parametric amplification that occurs when the cell in the resonator is short in length and is properly placed in the resonator. We note that in the nonstationary regime the required phase relations for the higher Stokes components are established immediately, since the thermal scattering produced when these components are formed can be neglected. This makes it possible to obtain synchronization by exciting the SMBS by short-duration pulses. Besides external beams, we can excite oscillations also by placing an active medium inside the resonator. It is obvious that if the resonator is long the scattering medium can be placed in several positions, defined in (1). To prevent excitation of anti-Stokes components, one of the resonator mirrors can be replaced by a Fabry-Perot etalon of small thickness, tuned in such a way that the frequency of the first anti-Stokes component falls in its transmission band. The absence of a saturating absorber inside the resonator makes it possible to make the resonator Q quite large. Quantitative estimates show that the SMBS can be excited by a laser with approximately 10 W power in the fundamental mode. The cell length can be 1 mm or less, corresponding to a pulse duration of several picoseconds. When SMBS is excited in a separate resonator, it is advisable to use the setup with the Fox-Smith resonator, as proposed in [2].

[1] V. N. Lugovoi and V. N. Strel'tsov, Zh. Eksp. Teor. Fiz. 62, 1312 (1972) [Sov. Phys.-JETP 35, 692 (1972)].

[2] F. A. Korolev, V. I. Odintsov, and E. Yu. Sokolova, ZhETF Pis. Red. 13, 112 (1971) [JETP Lett. 13, 77 (1971)].