Colliding-enhanced Cr:LiSAF broad-band phase-conjugate resonator

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A novel colliding-enhanced Cr:LiSAF broad-band phase-conjugate resonator (PCR) has been investigated theoretically and experimentally. This kind of PCR is a low initiating threshold resonator. It can produce self-Q-switching narrow pulse with about 35 ns duration (FWHM), efficiently correct intracavity phase aberrations, and severalfold improve output laser beam quality.

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Stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) are chosen largely as the phase-conjugation mirror, people often use them in a primary optical cavity to form a phase-conjugate resonator (PCR), which not only can correct aberrations and obtain low-divergence output laser beam, but also can limit the bandwidth of the oscillating radiation[1].

PCR is initiated by the most strong spike of free-running relaxation oscillation spike-series of primary cavity. So reducing the initiating threshold of PCR is the key to improve PCR's output energy. The initiating threshold of conventional PCR with linear primary resonant cavity is always very high[2], especially for the broad-band PCR[3,4]. In order to reduce the initiating threshold of Cr:LiSAF broad-band PCR, we have designed and operated a new colliding-enhanced broad-band PCR with ring primary resonant cavity. In the primary ring resonator, a beam-splitter (BS) splits the free-running beam into two sub-beams containing many sub-spikes, and ensures that two sub-spikes split from a same spike counterpropagate collide with the same intensity and phase in the middle of Brillouin-medium cell. So we realize the peak-to-peak colliding interaction and efficiently reduce the initiating threshold of PCR.

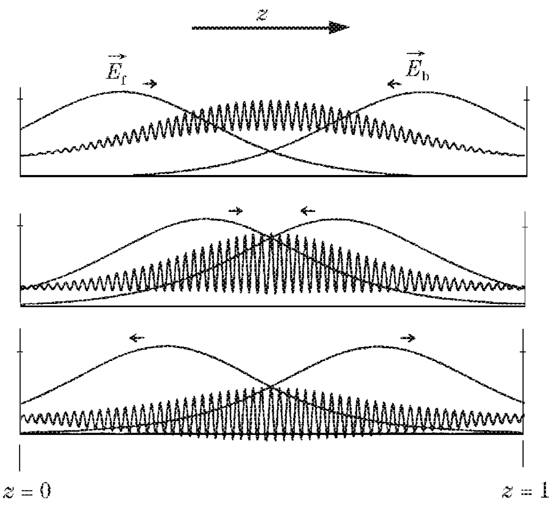

Fig. 1. The process of colliding interaction of two counter-propagating pulse waves and the build-up of acoustic wave refractive index grating in Brillouin medium.

As shown in Fig. 1, two counterpropagating laser pulse waves collide in a Brillouin medium. We assume that the total optical field within the Brillouin medium can be represented as the sum of the forward-going and backward-going plane-wave components as

$$E_{\mathrm{T}}(z,t) = \frac{1}{2}E_{\mathrm{f}}(z,t)\exp[i(kz-\omega t)$$
$$+\frac{1}{2}E_{\mathrm{b}}(z,t)\exp[i(-kz-\omega t)] + c.c.$$

here E_{f} and E_{b} are the complex amplitudes of forward-going and backward-going wave, respectively, ω is angular frequency, and k is their wave vector.

Owing to the process of eletrostriction, the local density of the medium is modified by the total optical field and forms an acoustic wave refractive index grating. We assume that the optical field and acoustic field obey the slowly varying amplitude approximation, thus can obtain the simplified wave equation[5]

$$\frac{\partial^2\rho}{\partial t^2} + \Gamma\frac{\partial\rho}{\partial t} + \Omega^2\rho = \frac{q^2\gamma}{8\pi}E_{\mathrm{f}}E_{\mathrm{b}}^*,$$

and the coupled amplitude equations for the forward- and backward-going waves

$$\frac{\partial E_{\mathrm{f}}}{\partial z} + \frac{1}{(c/n)}\frac{\partial E_{\mathrm{f}}}{\partial t} = i\kappa\rho E_{\mathrm{b}},$$

$$\frac{\partial E_{\mathrm{b}}}{\partial z} - \frac{1}{(c/n)}\frac{\partial E_{\mathrm{b}}}{\partial t} = -i\kappa\rho^* E_{\mathrm{f}}, \qquad (1)$$

here γ is the electrostrictive constant, $q = 2k$ is the resultant wave vector of total optical fields, $\Omega = qv$ is the Brillouin frequency, v is the velocity of light in the medium. $\Gamma = (4\eta/3\rho_0)\,q^2$ is the Brillouin linewidth , η is the viscosity, ρ_0 is the mean value of medium density. n is the refractive index of the medium, c is the velocity of light in the vacuum, and $\kappa = \gamma\omega/4\rho_0 nc$ is the coupling coefficient.

Several theoretical and experimental investigations have shown that counterpropagating laser beams in a Brillouin medium can lead to very complicated instability of the intensities of the transmitted waves. The origin of this instability is combined action of the gain experienced by the sidemodes to the input fields and of the distributed feedback due to scattering from the grating, which is formed by the interference between the two input fields. That is to say, it includes the normal SBS gain owing to the presence of the backward pump wave, the scattering of the backward-Stokes wave from the refractive index variation associated with standing-wave pattern created by the interference of counterpropagating pump waves, and the FWM process arising from the scattering of the backward pump wave resulting from the retreating acoustic wave driven by the interference between the forward pump wave and the backward anti-Stokes wave[5]. It is known that the Brillouin interaction leads to strong coupling among the interacting waves, and the great strength of this coupling can lead to this same instability in the standard SBS and FWM processes. The theoretical and experimental investigation have shown that two counterpropagating pump laser waves with an optimal wave mismatch can reduce the SBS threshold severalfold[6].

According to the above theoretical and experimental investigations, we have designed a novel colliding-enhanced PCR, as shown in Fig. 2. Here M_1, M_2, M_3 are 780 – 920 nm band reflection-coated mirrors with 100% reflectance, F_1 and F_2 are 5-cm focal length double-face antireflection-coated lens with 99% transmittance. BS is a dielectric-coated 45° beam-splitter, its reflectance and transmittance at 850-nm central frequency are 50%. M_2 and M_3 are symmetrical about the optical plane of the BS. The Brillouin-cell containing CCl_4 medium is placed at the middle point of the light path between M_2 and M_3. The length of Cr:LiSAF laser rod is 70 mm and its diameter is 6 mm. The pump source is Xe-flashlamp.

Here, the primary ring resonator is a compound optical resonator consisting of two coupled cavities. Under the condition of free-running of primary ring resonator, there are two resonant light paths, the first is $M_1 \rightarrow$ Cr:LiSAF $\rightarrow$ BS (transmitting) $\rightarrow M_3 \rightarrow$ Brillouin-cell $\rightarrow M_2 \rightarrow$ BS(reflecting) $\rightarrow$ Cr:LiSAF $\rightarrow M_1$, and the second is $M_1 \rightarrow$ Cr:LiSAF $\rightarrow$ BS (reflecting) $\rightarrow M_2 \rightarrow$ Brillouin-cell $\rightarrow M_3 \rightarrow$ BS (transmitting) $\rightarrow$ Cr:LiSAF $\rightarrow M_1$. The BS splits free-running beam into two equal sub-beams containing many sub-spikes, then they are focused from opposite sides into the Brillouin-cell by F_1 and F_2. When one of free-running spikes circulating in the primary ring resonator reaches an energy threshold, the two sub-spikes split from this strong spike will counterpropagate and collide with same intensity and phase in the focal area of F_1 and F_2. They will do peak-to-peak colliding interaction, produce easily forward- and backward-going phase-conjugate beams, and then the Brillouin-cell will become immediately a double-face-reflecting phase-conjugate mirror ($M_{\rm pc}$). At this time, the primary ring resonator changes rapidly into the colliding-enhanced PCR. This PCR is also a compound resonator consisting of two coupled cavities with two resonant light paths, the first path is $M_1 \rightarrow$ Cr:LiSAF $\rightarrow$ BS (transmitting) $\rightarrow M_3 \rightarrow M_{\rm pc}$ (phase-conjugate reflecting) $\rightarrow M_3 \rightarrow$ BS (transmitting) $\rightarrow$ Cr:LiSAF $\rightarrow M_1$, the second one is $M_1 \rightarrow$ Cr:LiSAF $\rightarrow$ BS (reflecting) $\rightarrow M_2 \rightarrow M_{\rm pc}$ (phase-conjugate reflecting) $\rightarrow M_2 \rightarrow$ BS (reflecting) $\rightarrow$ Cr:LiSAF $\rightarrow M_1$. Half of the energy in resonant cavity is reflected and transmitted from the side of the BS to provide the output of laser resonator.

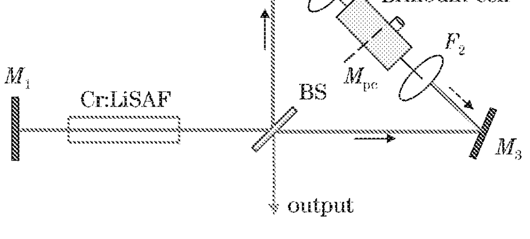

Fig. 2. Schematic diagram of the colliding-enhanced Cr:LiSAF broad-band PCR and its primary ring resonator.

In the resonant cavities, during the initiating process of colliding-enhanced PCR, the divergence of the non-phase-conjugate beams, such as the part of free-running beams which transmit through $M_{\rm pc}$, become higher and higher. While the divergence of the phase-conjugate beams, such as the backward-going Stokes and anti-Stokes beams, keep very low all the time. When they circulate in cavities, the non-phase-conjugate beams' energy loss is larger than their gain, they will be damped swiftly, but when the phase-conjugate beams' energy gain is larger than loss, they will be amplified rapidly. This ensures that colliding-enhance PCR forms easily, and its output beam quality is very high.

At 800-V Xe-flashlamp pump voltage, the free-running spikes energy in primary ring resonator do not reach the initiating threshold of PCR, so its output is a free-running relaxation oscillation spike series, which is distributed in 40 μs among approximately 10 spikes, each of ~300-ns duration (FWHM), as shown in Fig. 3. When increasing the pump voltage to 900 V, the free-running spike energy in primary ring resonator reaches the initiating threshold of PCR, the output of colliding-enhanced PCR is a single self-Q-switching pulse with about 35-ns duration (FWHM), as shown in Fig. 4.

We have also investigated the spatial characteristics of the output beam of primary ring resonator and colliding-enhanced PCR with a CCD camera. Under the same conditions, such as keeping the distance 3.0-m between the BS and CCD head, we have obtained their far-field

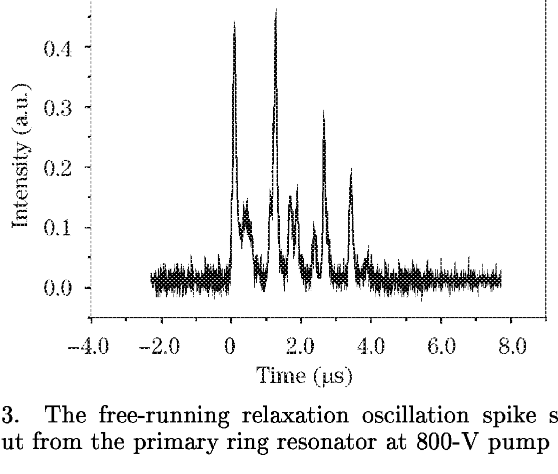

Fig. 3. The free-running relaxation oscillation spike series output from the primary ring resonator at 800-V pump voltage.

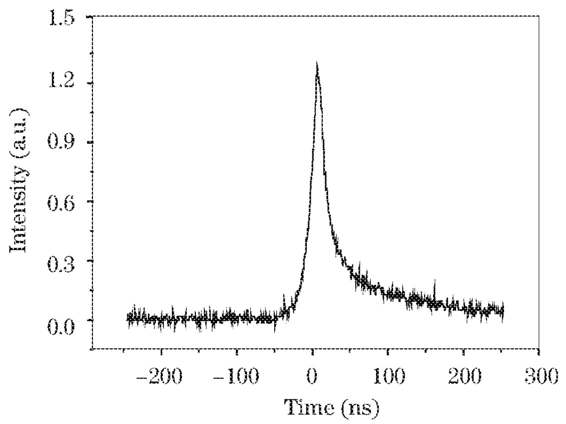

Fig. 4. The self- Q-switching laser pulse output from the colliding-enhanced PCR at 900-V pump voltage.

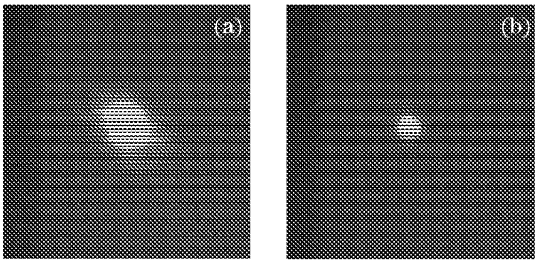

Fig. 5. The far-field spatial profile CCD photographs of output laser beam from (a) the primary ring resonator and (b) the colliding-enhanced PCR.

spatial profile CCD photographs, as shown in Fig. 5. Figure 5(a) is the beam far-field spot of primary ring resonator, and Fig. 5(b) is the far-field spot of colliding-enhanced PCR. By comparison of the far-field spot size with near-field spot size, we have measured their beam divergence angles, on an average, the former is about 4.0 mrad, and the latter is about 1.5 mrad.

In conclusion, we have theoretically and experimentally investigated a novel colliding-enhanced Cr:LiSAF broad-band PCR. In its primary ring resonant cavity, we let two counterpropagating free-running spike series with same intensity and phase collide within the CCl_4 Brillouin medium cell to initiate the colliding-enhanced PCR. By comparison with conventional linear PCR, we know the colliding-enhanced PCR is a low initiating threshold resonator, its output pulse is a self-Q-switching narrow pulse with about 35-ns duration (FWHM). It can correct efficiently intracavity phase aberrations, and improve output laser beam quality. In addition, we have noted that the mechanism of this colliding-enhanced PCR includes SBS and FWM processes.

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