Paper

Laser with SBS Pulse Compression for LIBS

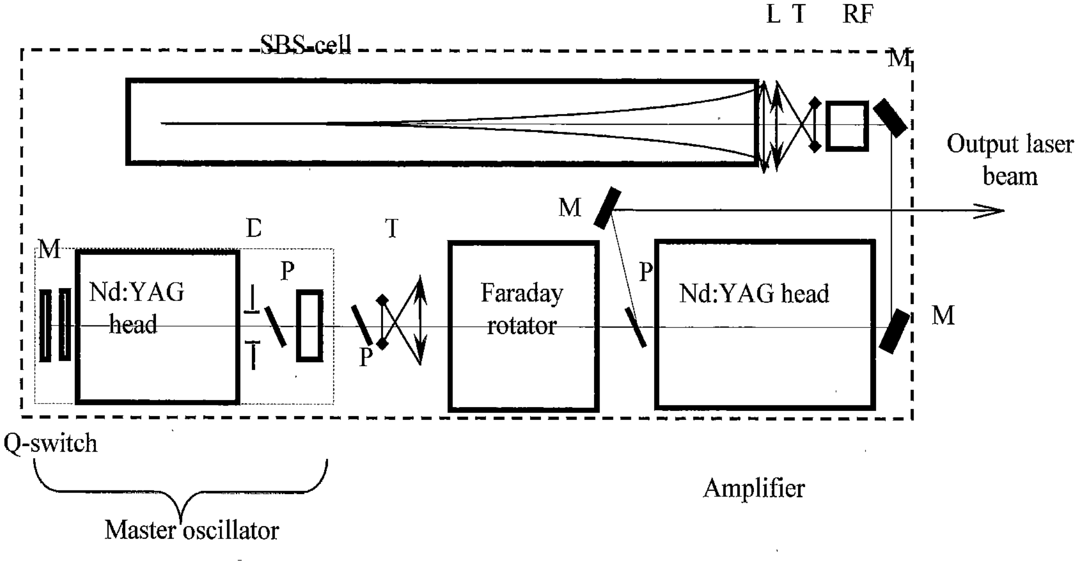
Member Toshitsugu Ueda (Yokogawa Electric Corporation)
Non-Member Vladimir Yashin (Institute of Laser Physics, Russia)
Non-Member Muneaki Wakamatsu (Institute of Laser Physics, Russia)
Non-Member Alexsander Andreev (Institute of Laser Physics, Russia)

High Intensity pulse laser is very important device as a light source of LIBS. For obtaining high peak power and short pulses, different approaches based on MOPA (Master Oscillator-Power Amplifier) scheme of master oscillator (MO) power amplifiers(PA) can be used. We use Stimulated Brillouin Scattering (SBS) cell in the power amplifier for laser pulse compression. Compression of pulses by SBS allows potentially receiving pulses by duration down to 100 picosecond and has following advantages. The compression of pulses at SBS have enough large power efficiency (usually more than 50 %), that is much higher than power efficiency of extracting of a short pulse, from a long "train" of mode-locked pulses or cutting of short pulse from a long Q-switched pulse. As a results, pulse duration of the laser which we have developed is less than 300ps at 50mJ out-put energy. This means that intensity of the laser is 20 times higher than conventional Nd:YAG pulse lasers.

keywords:Laser, Pulse laser, SBS, LIBS, Compression, Nd:YAG

1. Introduction

We are developing HPPL (High Peak-power Pulse Laser) as a light source of LIBS (Laser Induced Breakdown Spectroscopy). For obtaining high peak-power short laser pulses, different approaches based on the MOPA scheme of master oscillator (MO) power amplifiers can be used [1]. Compression of pulses by stimulated Brillouin scattering



M: mirrors; P: polarizer; T: telescope; D: diaphragm; RF: Fresnel's rhomb

Fig. 1 Schematic of laser system

(SBS) offers the potential of receiving pulses of duration down to 100 picosecond and has some advantages [2,3]. The compression of pulses for SBS has sufficiently large power efficiency (usually more than 50%) that is much higher than the power efficiency of extracting a short pulse from a long "train" of mode-locked pulses or cutting of short pulses from a long Q-switched pulse. As a result of the threshold nature of SBS, the compressed pulse has a very high contrast ratio (ratio of a pulse's peak intensity to the intensity of background) in comparison with pulses received by other methods.

The results of our theoretical and experimental investigations have shown the possibility to use SBS compression for creating pulse-periodic lasers with sub-nanosecond pulse duration and high beam quality. This construction, amplifier with SBS cell is especially suitable to compensate beam distortion, because SBS works as a phase conjugate mirror.

2. Description of laser system

A prototype laser system for improving separate elements was created and the optical scheme of the whole laser system was designed. The optical scheme of the laser system is shown in Fig. 1. The Q-switched master oscillator on a rod of Nd:YAG Ø3x60 mm generated a first transverse mode and transform limited pulse of duration 3 ns. The length of a MO cavity was selected as minimum L=11 cm A limited diameter of the cavity's transverse mode of a flat resonator is approximately d = 1 mm, which corresponds to the Fresnel number of $F=d^2/4\lambda L<1$. The transverse mode of such size was formed by the intracavity aperture. The Q-switch is accomplished by a passive switch with initial transmission of 30%. For selection of longitudinal modes, a Fabry-Perot interferometer is used, which also operates as an output mirror. The linear polarization of radiation was set by an interference thin-film polarizer. The output pulse energy was 1.5 to 2 mJ at the electrical pumping energy of about 30 J. The pulse repetition rate could be varied from 20 Hz down to 1 Hz. At reduction frequencies of less than 10 Hz, minor adjustment of the resonator's mirror is required.

After the master oscillator, the beam diameter is increased 3.5 times by a telescope to adjust it to the diameter of the Nd:YAG rod in the amplifier. The laser beam is then passed through a Faraday cell and directed at a laser amplifier on an Nd:YAG rod of Ø5x65 mm. The Faraday rotator on a permanent magnet serves to protect the MO against back-reflected depolarized radiation. Without the Faraday rotator, this radiation is reflected from the MO mirror, amplified again, and reflected from the SBS mirror. As a result, an additional parasitic pulse appears on the output of the laser system. The Faraday rotator removes this parasitic pulse entirely. After the first pass through the amplifier, a pulse of approximately 10 to 15 mJ energy passes through a Fresnel rhomb, through the telescope, then is focused by a lens onto the SBS cell. The Fresnel rhomb converts linear polarization into circular polarization, and on a back pass again converts the polarization back to linear. Radiation with such polarization is reflected from a polarizer and is emitted from an amplifying system.

The additional telescope serves to decrease the angular divergence of radiation and reduction, and thus increases the beam waist at the focus of the lens. Pulse compression takes place when a pulse is focused on the SBS cell, which is a key element of a laser system with pulse compression. Therefore we shall consider in more detail the requirements of the SBS compressor.

To obtain a high reflection coefficient from the SBS mirror it is essential to exceed (by 5 to 10 times) the threshold power of SBS, which for a Gaussian beam in the stationary condition of scattering is given by:

$$P_{th}=25/gk, \qquad (1)$$

where 25 is threshold increment of SBS, g is SBS gain coefficient,

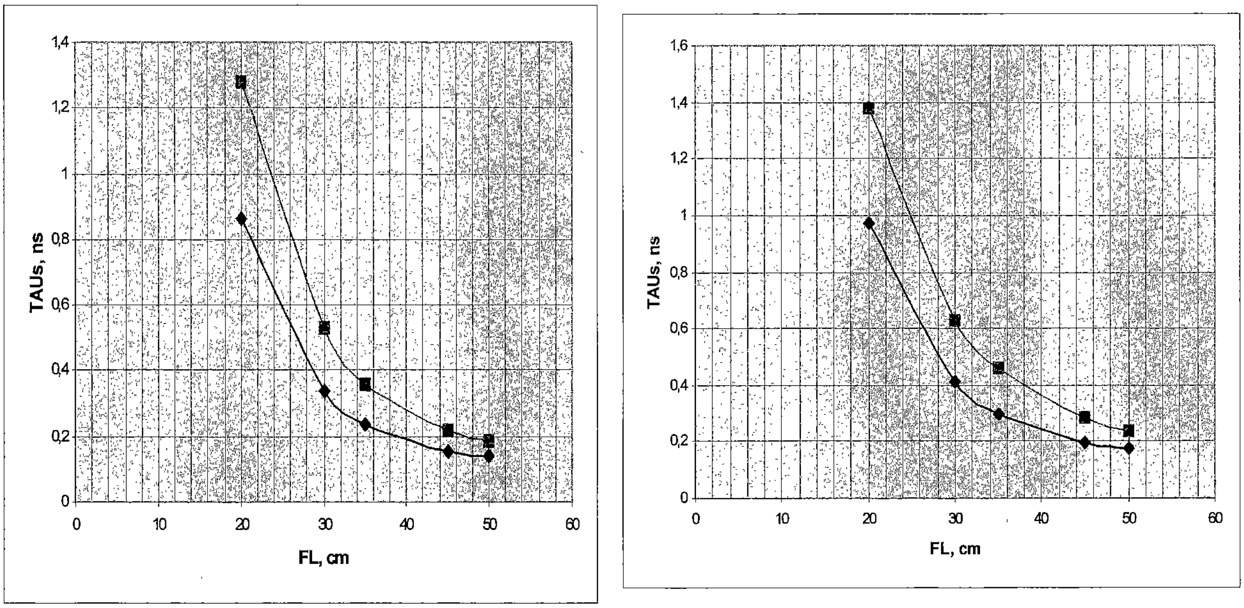


Fig. 2. Calculated duration of compressed pulse in CCl_4 as a function of focal length of focusing lens for input laser energy of 10 mJ (left picture) and 15 mJ (right picture) and for input pulse length of 3 ns (upper curves) and 2.5 ns (lower curves)

and $k=2\pi/\lambda$ (wave number).

To decrease the threshold energy of SBS and also to achieve effective pulse compression, it is necessary to minimize the sound relaxation time, which is an important parameter, of the SBS active medium.

For operation at a large pulse repetition rate, the SBS non-linear medium should have small absorption to prevent the development of thermal self-defocusing, which degrades the quality of reflected radiation. The parameter describing this effect is the critical energy of thermal self-action W_{cr}, which is defined by the expression:

$$W_{cr} = \frac{\rho c_p \lambda^2}{2\pi \beta n_T'} \qquad (2)$$

where ρ, c_p, β, and n_T are density, heat capacity, absorption coefficient, and derivative of refractive index with respect to temperature, respectively, and λ is radiation wavelength. Note that media with high W_{cr} must have low absorption coefficient and weak dependence of the refractive index on temperature. At present, there are refined media with W_{cr}>0.1 to 1 J, which are able to operate with long high-energy laser pulses.

When a laser operates with high pulse repetition rate, the heat in the lens caustics may accumulate steadily if the period of pulse repetition T is less than the time of medium heat relaxation in the lens caustics $t_r=d^2c_p\rho/4\chi$, where χ is heat conductivity, $d=\theta F$ is diameter of caustics for a lens with focal distance F, and θ is angular divergence of radiation at the input to the SBS mirror. In this case, the reflected radiation parameters may worsen some time after the laser starts to function. The situation may be complicated when a gas or liquid non-linear media with substance convection is used. The main method used to suppress this undesirable effect is to use a pure medium with large coefficient of heat conductivity and to scan the beam over the medium volume to avoid heat accumulation.

Processes such as optical breakdown, self-focusing and stimulated Raman scattering (SRS) should not be excited in the SBS cell.

It is clear that such liquids as CCl_4, $SiCl_4$, and $C_{18}F_{18}$ etc. are most suitable for producing subnanosecond laser pulses with mJ energy level. Solid-state media have a too high SBS threshold, whereas gaseous media have a large relaxation time of sound. Therefore we selected readily accessible purified liquids CCl_4 and $SiCl_4$ for application in our laser system.

Let us now consider the selection of SBS cell length and geometry of focusing for effective pulse compression down to the required duration. For effective compression, the round trip time in the SBS cell must not exceed the duration of the initial laser pulse t_p: $L>ct_p/2n$, where n is the index of refraction of non-linear media.

For our 3-ns laser pulse length SBS cell, the length should not exceed approximately 40 cm. We used SBS cells with CCL_4 of length 40 cm, and with $SiCl_4$ of length 50 cm.

The optimal focusing geometry must also be selected for obtaining a pulse of minimum duration. A short pulse of the Stokes frequency originates in a caustic of a lens, and then is amplified towards a pump pulse. Thus, to obtain a pulse of minimum duration $t_c \approx l_F/cn$ it is necessary to minimize the length of a caustic l_F, which is given by $l_F \approx F^2\theta/a$, where θ is angular divergence of radiation, and a is radius of laser beam on a focusing lens with focal length F.

Thus, to decrease the duration of a compressed pulse it is necessary to increase the radius of laser beam a, which is achieved by providing a 3x telescope before the SBS cell.

For more precise optimization of SBS compressor parameters, computer simulations of SBS compression in CCl_4 and $SiCl_4$ were conducted by the code described in the paper[3]. The calculations of

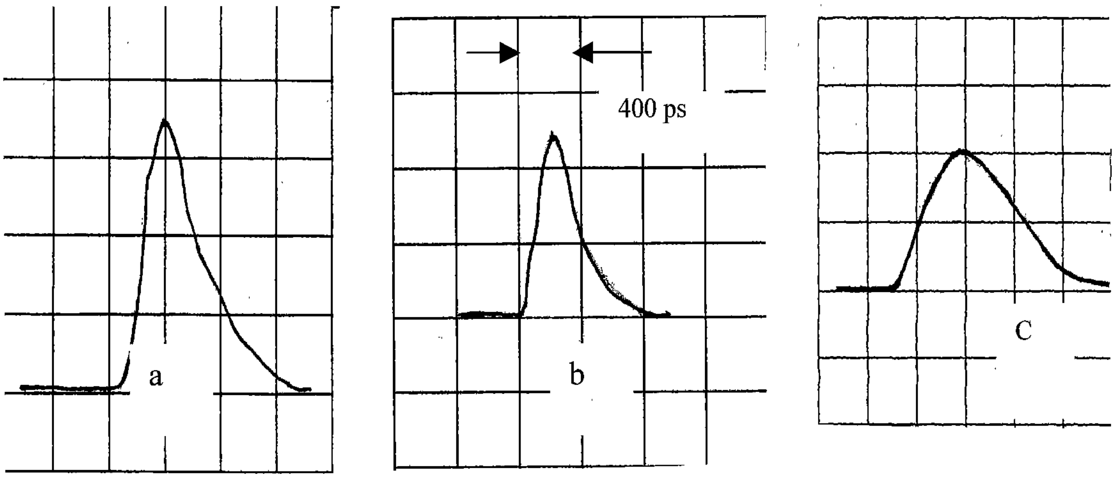


Fig. 3. Shapes of output pulses with energy 50 mJ under SBS compression in CCl_4 (a, c) and $SiCl_4$ (b) with focusing on SBS cell by lens with F=45 cm (a, b) and 12 cm (c).

the duration of a reflected pulse depending on the focal length of the lens are presented in Fig. 2. The results demonstrate that for a given non-linear medium, an initial pulse duration of 3 ns for the selected geometry of a focusing, the pulse duration less than 300 ps can be obtained. Note that by using a focusing lens of different focal distance, the duration of the compressed pulse can be changed. This capability is another advantage of pulse compression by SBS.

After reflection from SBS mirrors, the laser pulse undergoes change of polarization in the Fresnel rhomb, passes through the amplifier. Another important non-linear process, limiting the energy of short laser pulses is a inflamentation. In this process, there are hot spots within the beam, the angular directivity of laser radiation is degraded and there is breakdown of filaments inside the optical elements in the laser system. A first approximation of the danger of this process can be estimated by a so-called "breakup integral" determined in ESU units by the formula:

$$B = \frac{8\pi^2 n_2}{\lambda c n}\int_0^L I(z)dz \qquad (3)$$

where n_2 is non-linear index of refraction of Nd:YAG, L is length of non-linear medium, and I is peak intensity of laser pulse.

Numerous experimental and theoretical investigations have demonstrated that the maximum acceptable value of the breakup integral is B=1.5-3 depending on the cleanness of the laser system.

To define the parameters of the laser system, we conducted numerical modeling. The code calculates the output energy as a function of the input energy on the basis of the Franz-Nodvik equation, and also the value of the breakup integral B assuming a flat top intensity on the cross section of the beam.

The calculation results are demonstrate that the value of the breakup integral does not exceed 0.4 at energy of 50 mJ. For a non-uniform distribution of intensity on the cross section, its peak value exceeds 3 to 4 times on average, giving a maximum value of B of approximately 1.5. This value does not exceed the maximum allowable value of B, but is already rather close to it.

Thus, the conducted calculations demonstrate, that it is possible to obtain a laser pulse with duration 300 ps and energy 50 mJon an output of Nd:YAG laser system with SBS pulse compression. At the same time for obtaining the greater energy it is necessary to increase diameter of laser beam or to change the optical scheme of a pulse compression.

3. Parameters of laser system

The following parameters of radiation were measured at the output of the laser system.

- Energy of laser pulses and their stability from shot to shot were measured by a detector (LabMaster Ultima, Coherent Co.).
- The duration and shape of laser pulses after the master oscillator were measured by a fast pin-diode and oscillograph (Tektronix TDS-744A, with bandwidth of 500 MHz), and at the output of the laser system by a fast photodiode (FK-19, temporal resolution of 70 ps) with an oscillograph (S7-9A, with bandwidth of 5 GHz).
- The size of the beam was recorded on thermo-sensitive photographic paper.
- The quality of the laser beam was measured in terms of its angular divergence by using diaphragms established at the focal point of a long-focus lens with F=170 cm.

The energy of pulses at the output of the laser could be varied from 30 to 80 mJ by changing the amplifier's pumping energy. The variation of energy was within 5% from shot to shot. Depolarization of radiation takes place when the laser operates at the repetition rate of 20 Hz and the depolarized component passes through quarter-wave non-reciprocal elements (Fresnel rhomb and polarizer) blocking only by the Faraday rotator. Measurements showed that the energy of this depolarized radiation is about 1 mJ and does not affect the operation of the laser system or parameters of output radiation. Conversely, eliminating the Faraday rotator causes a spurious laser pulse in the output of the system and frequent optical breakdown of non-linear SBS media.

Oscilloscope images of the pulse shape are shown in Fig. 3. As is clear from these figures, application of CCl_4, and $SiCl_4$ gives the pulses with duration of less than 300 ps for a lens of focal length F=45 cm. Using a lens of shorter focal length F=12 cm increases the duration up to 800 ps. Thus, in the given laser system with SBS pulse compression, the duration of the output pulse can easily be controlled by changing the focal length of the lens.

As is clear from the measurements, more than 70% of the energy is contained within the diffraction angle of the laser beam of diameter 4 mm, compared with 83% in the limiting case of an idealized beam. This means that $M^2 < 1.2$. The angular divergence did not change upon decreasing the pulse repetition rate, thus showing that the thermal lens in the Nd:YAG rod of the amplifier was corrected by implementing phase conjugation in the SBS cell.

Operation of the laser system at the repetition rate of 20 Hz for 1 hour did not result in the appearance of self-focusing filaments inside the Nd:YAG rod, indicating the absence of disastrous small-scale instability. The lifetime of the laser system is determined by the lifetime of the flash lamps INP Ø5x60 used in the MO and amplifier. According to data of the manufacturer, the lifetime is $N=5\times10^6$ shots at the repetition rate of 20 Hz.

4. Conclusion

The results of our analytical and experimental researches have demonstrated the potential of using SBS compression for creating pulse-periodic lasers with subnanosecond pulse duration and high beam quality. Numerical modeling and experimental testing were conducted to optimize the scheme of the laser and obtain radiation with the required parameters. The scheme of a master oscillator and power amplifier (MOPA) allows the output pulse energy to be varied, and the pulse duration can be varied by changing the focal conditions. This allows flexible variation of radiation parameters, which could be useful for similar laser applications in such areas as laser breakdown spectroscopy, remote sensing, laser plasma generation, and creation of X-ray and EUV sources.

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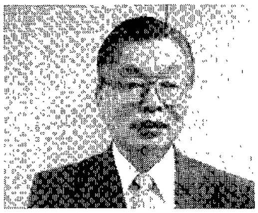
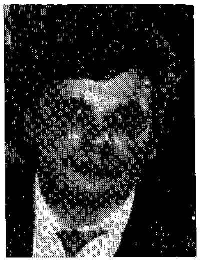
Toshitsugu Ueda (member)



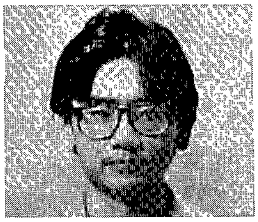
Toshitsugu Ueda was born in Nara, Japan, on October 4, 1945. He received the B.E. and M.E. degree in electrical engineering from Shinshu University, Nagano, Japan, in 1969 and 1971 respectively. He received Ph.D. degree from Tokyo Institute of Technology in 1988.
Since joining Yokogawa Electric Corporation in 1971, he has been engaged in developing low noise amplifiers, mechanical resonators, micro machining technologies and sensors using above mentioned technologies for temperature, pressure and displacement. Now he is a general manager of Corporate R&D department.
He received Awards from Society of Instrument and Control Engineers of Japan in 1987 and 1994, and Awards from Japan Institute Invention and Innovation in 1985 and 1987. Dr. Ueda is a member of the Institute of Electrical Engineers of Japan, and Society of Instrument and Control Engineers of Japan.

Vladimir Yashin (Non-member)



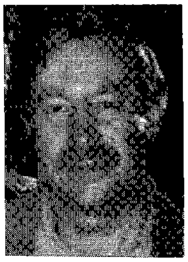
Vladimir Yashin was born in Gorkii, Russia, on April 8, 1951. He received the B.E. and M.E. degree in physics from Gorkii State University, Gorkii, Russia, in 1971 and 1973 respectively. He received PhD degree from Vavilov State Optical Institute, St. Petersburg, Russia in 1981. Since joining Vavilov State Optical Institute in 1973 he has been engaged in research and development of high power lasers. Now he is a chief of the laboratory in the Institute of Laser Physics, St. Petersburg, Russia. He is co-author of more than 80 publications and the book. Dr. Yashin is a member of ROS, SPIE and OSA.

Muneaki Wakamatsu (Non member)



Muneaki Wakamatsu was born in Tokyo, Japan, on August 25, 1965. He received the B.E. and M.E. degree in electrical engineering from Tokyo University of Aguriculture and Technology, Tokyo, Japan, in 1988 and 1990 respectively.
Since joining Yokogawa Electric Corporation in 1991, he has been engaged in developing IC tester and bare-board tester.

Alexander Andreev (Non-member)



Alexander Andreev was born in Moscow, Russia, on November 11, 1949. He received the B.E. and M.E. degree in physics from Leningrad State University, Leningrad, Russia, in 1970 and 1972 respectively. He received Ph.D degree from the same University in 1979. He received Doctor of Science degree from Vavilov State Optical Institute, St. Petersburg, Russia in 1991. In 1993 he got the position of professor from State Technical University of St. Petersburg. Since joining Vavilov State Optical Institute in 1972 he has been engaged in research and development of high power lasers and their applications. Now he is a chief of theoretical laboratory in Institute of Laser Physics, St. Petersburg, Russia. He is co-author of more than 100 publications and two books. Prof. Andreev is a member of ROS, SPIE and OSA.