Laser interferometer with wavefront-reversing mirrors

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A theoretical and experimental investigation was made of a Michelson interferometer with wavefront-reversing mirrors based on stimulated Brillouin scattering. It is shown that the period of the interference pattern obtained when the length of one of the interferometer arms is varied represents the frequency shift due to the stimulated scattering; the visibility curve tends to approach the limit 0.25 and represents a combination of the correlation functions for radiations with different path lengths corresponding to single and double transits across the difference between the interferometer arms. The interferometer can be used for any spatial structure of the exciting radiation and it is insensitive to the optical quality of its components.

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1. INTRODUCTION

Reversal of laser radiation wavefront by nonlinear optics methods is attracting considerable attention. This is primarily due to the unique properties of the radiation reflected from wavefront-reversing mirrors, whose field is identical (apart from the phase factor) with the complex conjugate of the incident-wave field:

$$E_{\text{refl}}(r_\perp) = \text{const}\, E^*_{\text{inc}}(r_\perp).$$

The operation of complex conjugacy is equivalent to reversal of the direction of time in the Maxwell equations and the reflected wave traveling in the opposite direction passes consecutively through all the states

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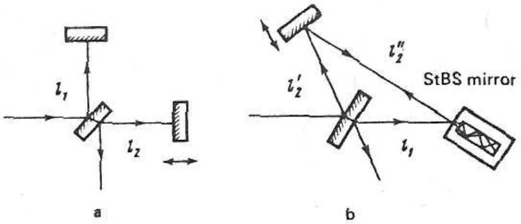

FIG. 1. a) Conventional Michelson interferometer with $\Delta l = l_2 - l_1$. b) Interferometer with wavefront-reversing Brillouin mirrors ($\Delta l = l_{2''} + l_{2'} - l_{1'}$).

of the incident radiation returning to the initial state. This is why wavefront reversal has been regarded so far mainly as a means for compensating phase distortions suffered by light waves in active elements of laser amplifiers, imperfect optical components, turbulent atmosphere, etc.

We shall show theoretically and experimentally that the use of wavefront-reversing mirrors based on stimulated Brillouin scattering (StBS mirrors) in conventional two-beam interferometers makes it possible to construct systems with new physical properties. By way of example, we shall consider the Michelson (or more exactly, the Twyman–Green) interferometer with plane-parallel light beams in Fig. 1a. In a classical version of this interferometer the waves reflected from the mirrors interfere in a semitransparent mirror and the intensity of the output radiation is given by

$$I \propto [1+\cos(\pi+\Delta\varphi)].$$

Here, $\Delta\varphi$ is the phase difference between two light beams acquired in the forward and reverse transits, amounting to $\Delta\varphi = 2k\Delta l$, where k is the wave vector amounting to $\sim 10^5\ \mathrm{cm}^{-1}$ in the optical range and Δl is the path difference between the interferometer arms.

We can easily see that the direct replacement of the conventional with the wavefront-reversing mirrors in interferometers of this type makes it possible to deal with spatially inhomogeneous instead of plane waves. The profiles of the amplitude of the reflected waves interfering in the semitransparent mirror are now identical and, in view of the relative nature of the field conjugacy on reflection, only the zeroth points may be displaced but the scale of the interference pattern remains the same. The use of two wavefront-reversing StBS mirrors has the effect that even in the case of monochromatic beams the phases of the reflected waves vary in an arbitrary manner from one laser shot to another[1] and, moreover, there may be fluctuations during a laser pulse with a characteristic time $\tau \sim \Gamma / 2\Delta\nu_{\mathrm{SpBS}}$ (Ref. 2), where $\Delta\nu_{\mathrm{SpBS}}$ is the width of the spontaneous scattering line and Γ is the gain increment of the scattered wave. This makes it more difficult to observe the interference pattern but also facilitates studies of fluctuations of the phase of the wave scattered in the stimulated Brillouin effect.[3]

Accidental variations of the phases can be eliminated by directing beams produced by division in a semitransparent mirror so they are reflected simultaneously by the same StBS mirror (Fig. 1b). An interferometer of this kind has fundamentally different characteristics from those discussed above. In fact, as pointed out before, a wavefront-reversing mirror performs an operation on the incident beams which is equivalent to time reversal. Therefore, a beam which has traversed a shorter path before reaching the reversing mirror is reflected with a phase lag amounting to $k\Delta l$ compared with the second beam. This delay would have been compensated in the reverse path had the frequency of light been unaffected by the reversing mirror and then the reflected beams would have arrived at the semitransparent mirror in phase for any value of Δl. However, since the Brillouin scattering produces a frequency shift of the Stokes component $\Delta\nu_B$, the reflected waves reach the semitransparent mirror with some phase difference amounting to $\Delta\varphi = \Delta k \Delta l = 2\pi\Delta_B \Delta l$ (the frequency shift is measured in reciprocal centimeters).

We can thus see that there is a fundamental difference between systems with independent mirrors and the system discussed above (Figs. 1a and 1b). In the former case a displacement of one of the mirrors by even a fraction of the wavelength alters considerably the difference between the phases of the light beams reaching the transparent mirror ($\Delta\varphi = 2k\Delta l$) because the absolute value of the wave vector is large. In the case of an interferometer with conventional mirrors it is also found that stringent requirements have to be satisfied in respect of the orientation of the mirror when it is displaced (scanned), in respect of its optical quality, and also in respect of the plane-parallel nature of the light beam. In the latter case of reflection of two light beams from the same wavefront-reversing mirror a change in the phase difference at the output of the interferometer with scanning of one of the arms is only due to a change in the frequency of light as a result of reflection. Since the frequency shift in StBS is small (10^{-2}–$10^{-1}\ \mathrm{cm}^{-1}$), the spatial period of the interference pattern amounts to centimeters. Moreover, in the case of reflection with wavefront reversal we can use light beams with any spatial structure and also low-quality beam splitters and mirrors.

Measurements of the interference pattern period can be used to determine the frequency shift in StBS. It should be pointed out that in this analysis it is assumed *a priori* that the laser and scattered radiations are monochromatic. Solid-state lasers with passive Q switching and without additional mode selection emit in practice lines of width $\Delta\nu_l = 0.1$–$0.1\ \mathrm{cm}^{-1}$, which is considerably greater than the width of the spontaneous scattering line of practically all the gases ($\Delta\nu_{\mathrm{SpBS}} \lesssim 10^{-3}\ \mathrm{cm}^{-1}$) and some liquids such as CS_2 ($\Delta\nu_{\mathrm{SpBS}} \sim 4\times10^{-3}\ \mathrm{cm}^{-1}$ at the neodymium laser wavelength). Therefore, relative to the active medium, we can regard laser radiation as wide-band: $\Delta\nu_l \gg \Delta\nu_{\mathrm{SpBS}}$. In a conventional interferometer when the difference between the paths of the two beams is $2\Delta l \to \infty$, the feasibility of the interference pattern becomes

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \to 0.$$

The behavior of the visibility curve in the case of an duce a spherical wave front with a radius of curvature as short as ~40 m. In any case, the phase offset is constant and reproducible from shot to shot; moreover, any dynamic changes in the individual optical path lengths are compensated for, as was seen by comparing Figs. 2(c) and 2(d).

In summary, we have demonstrated a practical technique for achieving laser energy scaling beyond traditional limits imposed by the maximum available volume of an active medium. This demonstrated energy-scaling technique, based on a phase-conjugate MOPA configuration, permits the coupling of several parallel amplifiers to form a single coherent output beam. The coherence is achieved despite dramatic differences in the individual amplifier energies and optical path lengths. Although the present work involves Nd:YAG as the active medium, the technique is quite general and can be applied to a variety of laser media. Moreover, the basic demonstration involving two parallel amplifiers can be readily scaled to much larger numbers.

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References

1. For a recent comprehensive review of nonlinear optical phase conjugation, see D. M. Pepper, "Nonlinear optical phase conjugation," in *The Laser Handbook*, M. Bass and M. Stitch, eds. (North-Holland, New York, 1985), Vol. 4.
2. N. G. Basov, V. F. Efimkov, I. G. Zubarev, A. V. Kotov, A. B. Mironov, S. I. Mikhailov, and M. G. Smirnov, Sov. J. Quantum Electron. **9,** 455 (1979).
3. T. R. O'Meara, Opt. Eng. **21,** 243 (1982).
4. V. G. Manishin and G. A. Pasmanik, Sov. J. Quantum Electron. **14,** 818 (1984).
5. D. A. Rockwell and D. N. Garrett, Proc. Soc. Photo-Opt. Instrum. Eng. **122,** 187 (1977).
6. N. G. Basov, I. G. Zubarev, A. B. Mironov, S. I. Mikhailov, and A. Yu. Okulov, Sov. Phys. JETP **52,** 847 (1980).
7. A. Yariv, *Quantum Electronics*, 2nd ed. (Wiley, New York, 1975), p. 496.
8. T. J. Greytak, "Spectrum of light scattered from thermal fluctuations in gases," Ph.D. dissertation (Massachusetts Institute of Technology, Cambridge, Mass., 1963) (unpublished).
9. V. S. Starunov and I. L. Fabelinskii, Sov. Phys. Usp. **12,** 463 (1970).

Coherent coupling of laser gain media using phase conjugation

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We have experimentally demonstrated a laser energy-scaling technique, based on a phase-conjugate oscillator/amplifier scheme, that permits the coupling of several parallel amplifiers to form a single coherent output beam. This coherence is achieved despite dramatic differences in the individual amplifier energies and optical path lengths. When many amplifiers are coupled together, energy can be scaled significantly beyond the limit imposed by the maximum available volume of a single active medium. Although the present demonstration utilized Nd:YAG, this technique is quite general and can be applied to a variety of laser media.

We report the demonstration of a practical technique for achieving laser energy scaling beyond traditional limits imposed by the maximum available volume of a single active medium. These limits can arise from fundamental laser characteristics, such as the occurrence of amplified spontaneous emission or parasitic oscillations, or they can arise from practical constraints of supporting technologies. Specific limitations of the latter type can be readily identified: (1) crystal growth technology sets a limit on the maximum boule size that can be achieved for any specific solid-state laser material, (2) practical constraints on any one of several technologies involved in electric discharge or electron-beam pumping limit the volume of large gas lasers, and (3) dissipating thermal loads becomes increasingly difficult as the volume of any laser medium grows.

The demonstrated energy-scaling technique reported here is based on a phase-conjugate master oscillator/power amplifier (MOPA) configuration. Previous work with such a configuration has established that phase distortions introduced by an optically distorted amplifier can be compensated for by using nonlinear-optical phase conjugation (NOPC).[1] The present work takes advantage of the fact that NOPC will also compensate for any phase distortions arising from optical-path-length differences among an array of parallel amplifiers. Hence several parallel amplifiers driven by a single oscillator can be coupled to form a single coherent output beam. This coherence is achieved despite dramatic differences in the individual amplifier energies and optical path lengths. The concept of using phase conjugation to achieve such coherent coupling has been mentioned[2–4]; however, the present work represents the first reported successful experimental demonstration. Although Nd:YAG was used as the active medium, the technique is quite general and can be applied to a variety of laser media.

The experimental arrangement is shown schematically in Fig. 1. The 9-mJ output of a single-mode Nd:YAG oscillator passes through a beam-expansion telescope and is directed into the amplifier leg by a thin-film polarizer. Because the beam is vertically polarized (i.e., normal to the plane of the figure), all the oscillator energy enters the amplifier leg. Following a quarter-wave plate is a 2× cylindrical telescope that produces an elliptical spot having major and minor diameters of 16 and 8 mm, respectively, with the major axis parallel to the plane of the experimental table. Through the use of several prisms, this elliptical spot is divided into two D-shaped spots, each of which passes through a different 7-mm-diameter Nd:YAG amplifier rod. Each rod is contained in its respective pump head. Following the amplifiers, the two beams (which are of circular cross section at this point) are aligned to be parallel and are focused into the same region of a phase-conjugate mirror (PCM). In this experiment the PCM is a cell containing 1500 psig of methane, and phase conjugation arises through the process of stimulated Brillouin scattering (SBS). The phase-conjugated beams retrace their respective paths through the amplifiers, where they are amplified a second time.

The two parallel round spots are converted into two elliptical spots as they pass back through the cylindrical telescope. Following a second pass through the

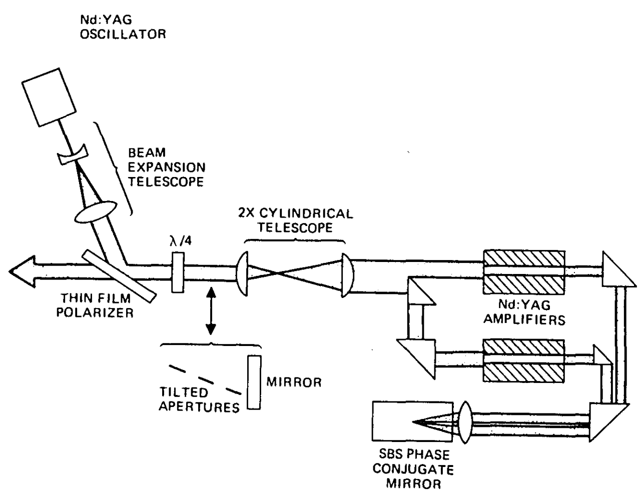

Fig. 1. Experimental arrangement used to demonstrate coherent coupling of parallel gain media using phase conjugation. Inserting mirror and tilted apertures as indicated provides a reference beam for comparison purposes.

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