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EFFECT OF PUMP-INDUCED BIREFRINGENCE IN NEODYMIUM GLASS ON LASER OPERATION

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Pump-induced distortion of the optical properties of neodymium glass and its effect on laser operation is studied experimentally. It is shown that birefringence induced in the glass by pumping can strongly affect polarization and spatial distribution of neodymium laser emission intensity. The conditions necessary to achieve uniform intensity distribution from neodymium glass lasers are considered.

INTRODUCTION

THE active element of solid-state lasers is known to change its optical properties upon heating by pumping emission.[1] Nonuniform absorption of pumping emission by a round laser rod generates a radial thermal gradient that generally speaking varies in time. This gradient in turn causes a change in the length and in the refraction index that is nonuniform over the rod cross section. It also generates mechanical stress and its consequence, birefringence in the active medium. Distortion of the optical length in the rod and birefringence affect the operation of solid-state lasers.

This effect is particularly noticeable if the active medium is neodymium glass with high optical uniformity and practically total absence of optical anisotropy in the unpumped state. The nonuniformity in the distribution of the optical path length over the rod cross section primarily affects laser emission divergence.[2-4] Birefringence induced by pumping contributes relatively little to the change in the optical path length[3-5] but can strongly affect the distribution of intensity over the laser beam cross section.[6]

Uniform distribution of intensity over the beam cross section and elimination of or compensation for the distortions in the optical path length are important factors in the achievement of maximum energy, power, and brightness of the output emission from a laser system. Insofar as the output energy and power of modern high-power laser systems are limited by damage to the active medium and self-focusing, the achievement of a uniform emission distribution over the cross section of the active element opens the way to maximum energy and power yields. The elimination of or compensation for the changes in the optical path length is the necessary precondition for maximum directivity of the laser system emission.

In this paper we investigate the effect of thermal distortions on the operation of a high-power neodymium glass laser.[6,7] We show that birefringence induced in the active medium by pumping strongly affects polarization and spatial distribution of neodymium laser intensity. The results of our research are used to consider the conditions that are necessary to obtain uniform intensity distribution over the beam cross section in neodymium glass lasers.

EXPERIMENTAL RESULTS AND DISCUSSION

1. We have previously described[6,7] high-power neodymium glass laser systems capable of generating light pulses up to 100 J with a length of ~5 nsec and up to 20 J with a length of $\sim 10^{-11}$ sec. These systems consisted of a driving oscillator and an amplifier, the latter containing rods cut at the Brewster angle.

No special measures were taken to eliminate or compensate for thermal distortion in the rods. The emission divergence at the output stage of the amplifier was $(3-6)\times 10^{-3}$ rad. It was not always possible to obtain a sufficiently uniform intensity distribution at the output from the laser system. Figure 1a shows a photograph of a strongly nonuniform intensity distribution. The cruciform emission trace was obtained on a photographic plate placed 0.5 m from the amplifier output. The more-or-less bright image of the cruciform intensity distribution was observed repeatedly both in the operation of the ultra-short pulse high-power laser[6] and in that of the nanosecond pulse laser.[7] Figure 1b shows a photograph of cruciform intensity distribution at the end face of the amplifier output stage.[6] One of the cross arms is always oriented in the polarization direction of the driving oscillator beam, while the other is perpendicular to the first. Such an intensity distribution causes a cruciform type of damage observed on the surface of the end faces and inside the rods. Figure 1c shows a photograph of damage distribution on the end face of the amplifier output stage rod.[7] This damage resulted from several tens of flashes.

We note another important factor revealed in the course of work with the high-power laser.[6] We expected that the degree of polarization of emission at the output will be close to 100%, since the amplified emission of the driving oscillator of ultra-short pulses passed through polarizers of the electro-optical shutter and then through 14 surfaces inclined at the Brewster angle to the amplified beam: 10 end faces of the amplifier rods and 4 end faces of bleaching dye cells used to decouple the amplifier. It was therefore assumed that an Iceland spar wedge can split the output beam in two with the same intensity distribution. It turned out how-

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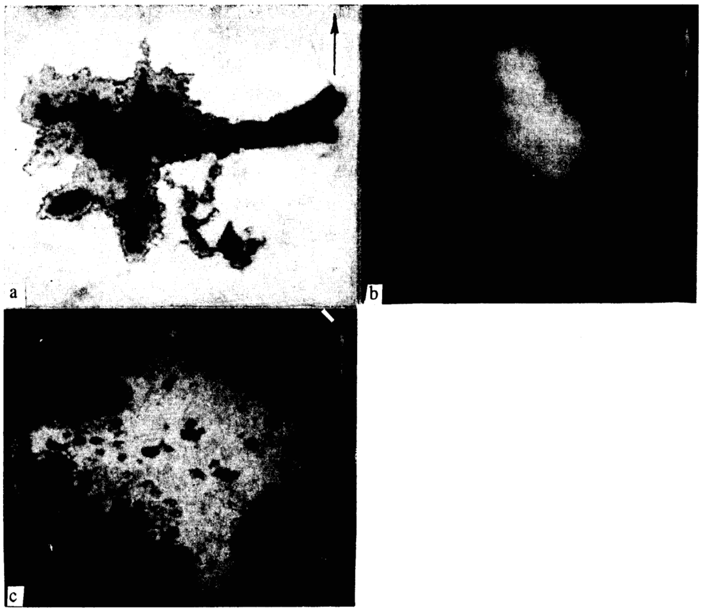


FIG. 1. a) Emission trace on a photographic plate 0.5 m away from amplifier output. b) Intensity distribution on the output end face of amplifier, c) Damage distribution on the output end face of rod $\phi 30 \times 650$ mm; a section of lateral surface of this rod was polished to observe internal damage. Arrow designates the direction of polarization of the driving oscillator beam.

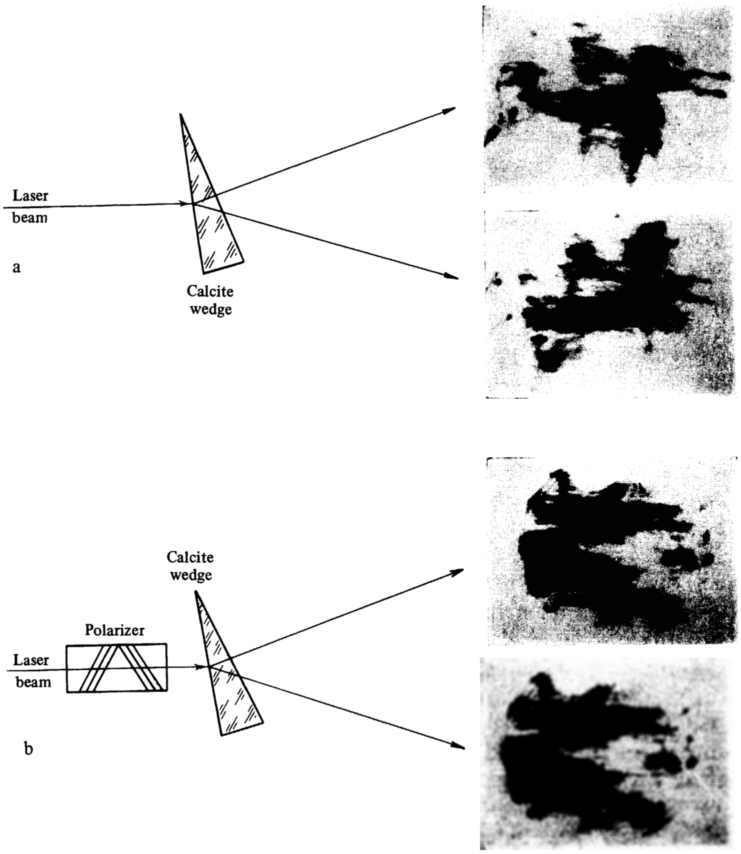


FIG. 2. Experimental observation of emission depolarization at amplifier output.

ever that the traces of the two beams showed different intensity distributions (Fig. 2a). At the same time the beam traces were similar when the beam from the amplifier output was allowed to pass through an additional polarizer (stack) installed ahead of the wedge (Fig. 2b). Although we made no quantitative measurements, the obtained result indicates a nonuniform distribution of emission with varying polarization over the cross section of the amplifier end face.

All the observed phenomena, such as the low directivity, nonuniform intensity distribution, and depolarization of the amplifier output emission, turned out to have the same origin. These phenomena are caused by distortion of the optical properties of neodymium glass due to nonuniform distribution of pump emission in the active rods.

We first consider the effect of nonuniform pump distribution on the divergence of laser systems.[6,7] As we know, it is difficult to obtain a sufficiently homogeneous (uniform) pump distribution over the entire

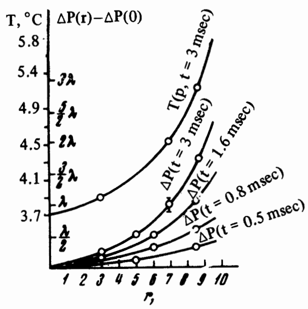
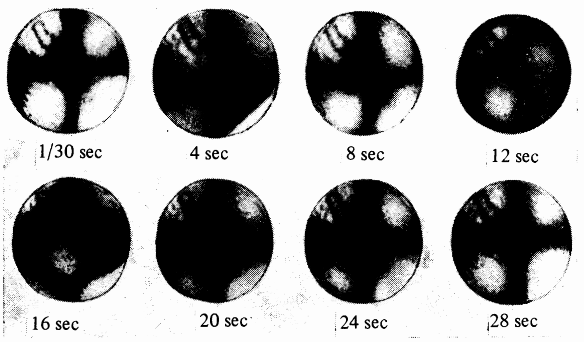


FIG. 3. Distribution of optical path length change $\Delta P(4)-\Delta P(0)$ and temperature increment $T(r)$ along the radius of a neodymium glass rod $\phi 20 \times 260$ mm pumped with ~10 Kj and housed in a reflector with four straight lamps, $\lambda = 0.63\mu$, r in mm.

cross section of the cylindrical neodymium glass rod.[8-13] The distribution of energy absorbed in the rod depends on the optical thickness of the specimen, rod diameter, neodymium ion concentration, lateral surface finish, and the ratio of refraction indices of the active and ambient media. Comparison with data from [8-13] shows that our conditions[6,7] call for pump distribution with maximum concentration at the rod periphery. To verify this we investigated the distribution of path length variation $\Delta P(r)$ along radius r of an LGS-28-2 glass rod (dimensions, $\phi 20 \times 260$ mm, concentration, 2% Nd_2O_3) in an IFP-5000 four-lamp reflector, using methods analogous to those reported in [1,3,4,8]. Figure 3 shows the functions $\Delta P(r) - \Delta P(0)$ for various pump times and the temperature increment distribution T(r) as a function of radius (a slight azimuthal nonuniformity of pumping was neglected) computed from these data. Rods with a distribution similar to that in Fig. 3 act on the laser beam as diverging lenses whose focal lengths depend on pump energy. Such lenses generated in our laser rods during pumping[6,7] degraded the divergence of laser emission.

We can now explain the origin of the cruciform intensity distribution (Fig. 1). The following experiment was performed to study the birefringence observed in the rods. A plane polarized parallel beam from a He-Ne gas laser, $\lambda = 0.63\,\mu$, operating either in a pulse mode[2)] or in a cw mode was collimated in a telescope and allowed to fall on a $\phi 20 \times 260$ mm specimen housed in a four-lamp reflector. The specimen was placed between crossed polarizer and analyzer. A series of pictures of intensity distribution of the emission that passed through the analyzer was made with an SFR camera during the pumping period (~3 msec) and with a motion picture camera during the cooling period (~5 min). Figure 4 shows the sequence of the motion picture frames. We see that the cruciform intensity distribution generated during pumping becomes distorted and reappears only after ~30 sec. Birefringence falls in ~5 min down to the initial low value determined by the intrinsic anisotropy of glass and distortions contributed by the rod holders. We can thus assume that similar phenomena occur in the amplifier when its own polarized laser emission passes through neodymium glass. The near-parallel polarized laser beam entered the amplifier[6,7] and "illuminated" its active medium, while the distributed polarizer consisting of Brewster end faces served as analyzer.


1/30 sec 4 sec 8 sec 12 sec

16 sec 20 sec 24 sec 28 sec

FIG. 4. Interference patterns due to birefringence in neodymium glass (observed in crossed polarizers). Time reckoned from start of pump lamps.

The cruciform intensity distribution occurring when a parallel laser beam passes through neodymium glass is due to the symmetry of mechanical stresses in the rod caused by the temperature gradient. An isotropically pumped long rod has a radially symmetric temperature gradient (see Fig. 3) and a radially-symmetric stress pattern. The pattern is described by equations that relate the radial $\sigma_r(r)$ and circumferential $\sigma_\varphi(r)$ stress components to temperature distribution functions T(r)[12,13,4,5]

$$\sigma_r(r) = \frac{E\alpha}{2(1-\gamma)}\,[\overline{T}(a) - \overline{T}(r)], \tag{1}$$

$$\sigma_\varphi(r) = \frac{E\alpha}{2(1-\gamma)}\,[\overline{T}(a) - \overline{T}(r) - 2T(r)], \tag{2}$$

where

$$\overline{T}(r) = \frac{2}{r^2}\int_0^r xT(x)\,dx$$

is the mean temperature within the rod limited by radius r, $\overline{T}(a)$ is the mean temperature over the entire cross section of the rod, E and γ are Young's and Poisson's moduli, and α is the coefficient of linear thermal expansion.

The radially symmetric distribution over the rod end face also has birefringence $\Delta n_{r\varphi} = \Delta n_r - \Delta n_\varphi$, due to stresses ($\Delta n_r$ and Δn_φ denote the changes in the refraction index of the medium under stress for a beam with radial and azimuthal polarization respectively). The value of birefringence is related to photoelastic constants $B_\perp$ and $B_\parallel$ of the material and to stress by

$$\Delta n_{r\varphi}(r) = \frac{\alpha E}{1-\nu}\,(B_\perp - B_\parallel)\,(T(r) - \overline{T}(r)). \tag{3}$$

Clearly, when a parallel plane polarized beam with homogeneous intensity distribution passes through the rod, birefringence is absent only in the case of beams propagating along two mutually perpendicular diameters, one of which is parallel and the other perpendicular to the direction of polarization. For the rest of azimuthal angles birefringence causes a variation in beam polarization as the beam propagates in the rod: in the general case the beam assumes elliptical polarization where the orientation and eccentricity of the ellipse are different for points on the output rod face having different azimuthal angles and distances from the center. Now if a beam with such a polarization pattern passes through an analyzer crossed with the initial direction of polarization of the beam the resulting intensity distribution

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[2)] The methodology of measuring thermal distortion in active media of solid-state lasers based on pulse-switched gas laser was developed by A. M. Leontovich and associates.

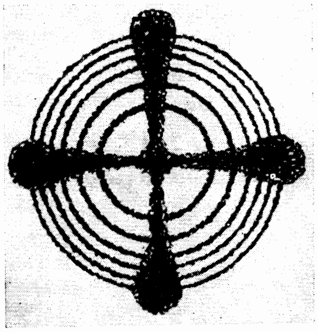

FIG. 5. Interference pattern of a uniaxial crystal in converging beams with crossed polarizers in a section perpendicular to the optical axis.

has the form of a "dark" cross surrounded by rings. This distribution resembles a conoscopic pattern, i.e., an interference pattern of a cone of polarized beams passing through a uniaxial crystal in crossed polarizers (Fig. 5) (see [14] for example). If the direction of analyzer transmission is parallel to the direction of polarization of the incident beam the intensity distribution is a negative complement of Fig. 5. This is the case that was obtained in earlier experiments.[6, 7] Thus the radiation that passed through the amplifier formed a "bright" cross when the distribution of stresses and birefringence had a radial symmetry (Figs. 1, 4). The absence of "bright" rings corresponding to the path difference of a whole number of 1.06 μ wavelengths can be attributed to the distributed nature of the polarizer. The emission intensity distribution at amplifier output had a different structure when asymmetric temperature gradients set in, generated by nonuniform cooling of rod surfaces with water (see Figs. 2 and 4). Consequently the occurrence of any given intensity distribution at amplifier output is determined by the length of the pause between two consecutive flashes.

We believe that the above mechanism explains the different intensity distributions observed in the laser beam at amplifier output.[6, 7] It also clarifies the origin and nature of emission depolarization at amplifier output (see Fig. 2). We note that depolarization at amplifier output in a high-power system was also observed in [15].

Pump-induced birefringence and cruciform intensity distribution of the probing gas laser light that passed through neodymium glass and crossed polarizers were first observed (after the end of the pump pulse) in [16]. In the case of strong temperature gradients cruciform patterns with rings were reported in [17] where the number of rings reached six. In our experiments a maximum of one ring was observed upon pumping a ϕ 20 × 260 mm rod (see Fig. 6 below). This allows us to evaluate the magnitude of birefringence in neodymium glass. We obtain $\Delta n_{r\varphi} \le 5 \times 10^{-6}$ from the condition $L\Delta n_{r\varphi} \le \lambda$, where L is the rod length and $\lambda \approx 10^{-4}$ cm. Using (3), data on temperature distribution in the rod (Fig. 3), and neodymium glass constants,[18] we obtain for $r = 0.9$ cm $\Delta n_{r\varphi} \approx 1.5 \times 10^{-6}$.

We can assume that the above mechanism producing cruciform emission intensity distribution occurs not only in the passage of plane polarized laser beam through the amplifier but also in neodymium glass oscillators operating with polarized radiation. In particular, such oscillators include some Q-switched oscillators and ultrashort pulse oscillators. Neodymium glass is known to be a sufficiently isotropic material; the magnitude of birefringence in domestic specimens of the glass is 1 – 6 nm/cm.[19] Therefore different polarizing elements are used to obtain completely or partially polarized neodymium laser emission. Such elements are electro-optical shutters with polarizing prisms, cells and plates set at the Brewster angle to the beam axis and, finally, end faces of active rods cut at the Brewster angle. Polarized emission from neodymium glass is usually needed in connection with the use of various shutters operating with polarized emission for the shaping of laser pulses.

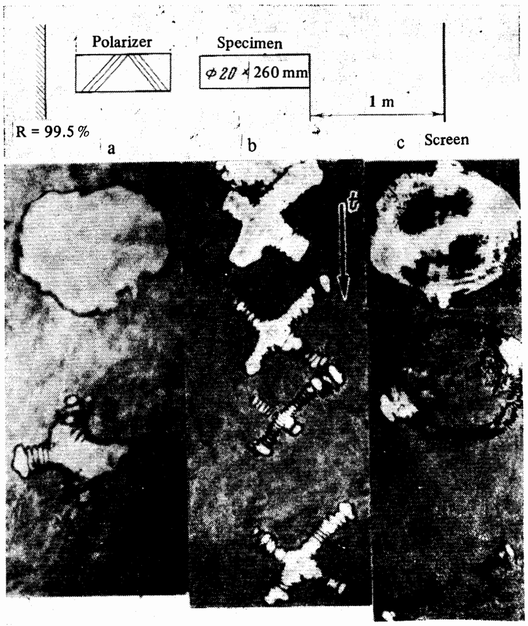

FIG. 6. Experimental observation of neodymium glass oscillator emission intensity distribution. Emission traces of neodymium glass oscillator for near-threshold pumping. a–single flashes (with stack); b–four flashes in succession at ~1 min intervals; stack in oscillator rotated through 45° relative to the preceding case; c–three flashes in succession at ~1 min intervals (without stack).

We investigated intensity distribution in the beam of an oscillator shown in Fig. 6. We used the same ϕ 20 × 260 mm rod and reflector as in the experiments with the gas laser. The resonator was formed by a mirror with a reflection coefficient R = 99.5% and the rod end face. The resonator contained a ϕ 15 mm stack providing 94% polarization; the stack could be rotated about the resonator axis. Figure 6 also shows screen (duplicating paper) images of oscillator emission; the screen was placed 1 m away from the output end face when pumping levels were close to the generation threshold (~10 kJ). The cruciform intensity distribution (Fig. 6a, bottom) well visible at threshold pump levels is masked by strong background radiation from the entire end face when pump level considerably exceeds threshold (Fig. 6a, top). The cruciform intensity distribution was particularly clear when flashes followed one another through ~1 min intervals; this is probably due to the increased radially symmetric stress in the active rod occurring in this mode of operation (Fig. 6b). The rotation of the stack through an angle was followed by the rotation of the cruciform distribution through a corresponding angle (Fig. 6c). We observed a more-or-less bright cruciform intensity distribution in the output emission of neodymium glass oscillators operating in various modes (free running, giant pulses, ultrashort pulses) whenever the oscillators contained rods with end faces cut at the Brewster angle. No other polarizing elements were inserted in the oscillator resonators. A polarizing element in the oscillator (stack or Brewster end faces) apparently serves simultaneously as analyzer and polarizer of the emission developing in the oscillator. In this sense the ordinary neodymium glass laser with two mirrors operating with polarized emission is analogous to the classical polariscope used in the study of photoelasticity.[20]

It is of interest to note that the effect of pump-induced birefringence on the emission intensity distribution can be observed even in the absence of any polarizing elements whatever in the oscillator resonator. Figure 6c shows the emission traces of an oscillator without the stack. The circular intensity distribution crossed by straight lines can be explained as follows. A slight azimuthal nonuniformity of pumping that occurred in the oscillator gave rise to preferred directions of stress in the rod. These are the principal directions of the polarizer and simultaneously of the analyzer of radiation developing in the oscillator. Under these conditions the circular generation region apparently corresponds to the region of localization of stress that creates a one-wavelength path difference in the rod for $\lambda = 1.06\,\mu$. Such a weak anisotropy in neodymium glass due to pumping inhomogeneity thus represents an emission selector in the oscillator in terms of polarization. At the generation threshold where the selector properties are particularly evident weak anisotropy should cause a strong polarization of the neodymium glass laser. Neodymium laser polarization of such an origin was probably already observed in some experiments.[21-23]

CONCLUSIONS

The experimental facts presented in this paper point to the strong effect of pump-induced birefringence on such laser characteristics as intensity distribution and emission polarization. These characteristics obviously affect other parameters of glass lasers to some extent: energy, emission divergence, etc. There is also no doubt that pump-induced birefringence can affect the characteristics of other solid-state lasers (preliminary results obtained with a ruby laser confirm this assumption).

As we noted it is difficult to achieve a complete elimination of stress due to temperature gradient in neodymium glass. Furthermore laser glass is always subject to stress generated during the preparation of active elements. Therefore when working with neodymium glass lasers one should always consider the possibility of deformation of intensity distribution and also of changes in emission polarization due to birefringence in the active medium. This caution is particularly applicable to laser systems with large active media.

Homogeneous emission intensity distribution in oscillators with rods cut at the Brewster angle can be obtained using diaphragms that limit a small light beam whose axis coincides with the least-stress direction in the rod. The use of diaphragms naturally causes loss of power, but it does improve the distribution homogeneity. A beam that is homogeneous over amplifier cross section means that the damage threshold in the active medium of the amplifier is reached simultaneously over the entire cross section. This is a significant factor in the control of emission power level in the amplifier. A homogeneous intensity distribution of the laser beam yields the maximum energy of output radiation whose value is determined by the strength of the active medium and its cross sectional area. It is also maintained[24] that homogeneous emission distribution over the end face of a neodymium glass rod increases the stability of glass with respect to self-focusing.

The currently widespread practice of working with high-power neodymium glass laser systems is based on the fact that the oscillator and amplifier employ rods cut at the Brewster angle. This end face treatment is known to ensure effective decoupling of amplifier stages and minimization of end face reflection losses in the oscillator and amplifier if the amplified emission is polarized in the plane of incidence on the end face. In view of the above, to obtain the most homogeneous distribution at the amplifier output we should reduce the number of amplifier rods, discs, and other optical elements that are inclined at the Brewster angle to the axis of the amplified beam. We must also use diaphragms to cut off the regions of the amplifier active medium with strongly nonhomogeneous temperature distribution. It is further desirable to use in the amplifier rods whose end faces are cut parallel to each other at a small angle sufficient to avoid self-excitation, and not rods cut at the Brewster angle. The formation of high-power plane-polarized emission in neodymium glass laser systems requires the use of rectangular rather than circular cross sections rods in the amplifiers. In such rods pumping generates predominantly linear (and not radial) temperature gradients and the effect of birefringence in the glass on polarization of emission that passed through the rod can be reduced by a suitable orientation of polarization direction of the incident radiation.[25]

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