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Prospects of solid state lasers for material processing

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Abstract. Since the invention of LASER in 1960, lasers have made a great impact in a wide range of scientific and technological applications. The first half of this paper discusses the basic differences between lasers and conventional heat sources and the second half is devoted to solid state lasers with specific reference to 'high average power' solid state lasers used in material processing. The various physical processes that influence their operation and the role of focusing optics are also discussed.

Keywords. Lasers; material processing; high average power.

1. Introduction

Since the invention of LASER in 1960, lasers have found wide use in a large number of applications, such as in basic research, communication, material processing, laser-induced fusion, particle acceleration, electronics, defence, and medicine and surgery. The demand on laser wavelength, power, pulse duration and repetition rate is dictated by the specific application. Each of these applications utilizes one or more of the interesting properties of lasers. The first half of this paper discusses the basic differences between lasers and conventional heat sources and the second half is devoted to solid state lasers with specific reference to 'high average power' solid state lasers used in material processing. The various physical processes that influence their operation and the role of focusing optics are also discussed.

2. Lasers vs thermal sources

Lasers differ from conventional sources in the following ways: (a) monochromaticity, (b) directionality, (c) coherence and (d) brightness (Siegman 1971).

2.1 *Monochromaticity*

To say in general that lasers are monochromatic is a misnomer. There are lasers with output spectral width of a few hundreds of angstroms, like, for instance, Nd: glass and dye lasers. Nevertheless, lasers can be operated to give very narrow emission width. The spectral purity $\Delta v/v_0$, where v_0 is the central frequency of emission and Δv the associated linewidth, can be as small as $\sim 10^{-11}$. The spectral width is decided by the number of oscillating modes. Even a laser oscillating in many axial modes is almost monochromatic with $\Delta v/v_0 \sim 10^{-5}$ to 10^{-4}. To provide better monochromaticity, lasers are forced to oscillate in single axial mode only. The frequency stabilization is obtained by vibration isolation, by temperature stabilization and by servo control of the mirror spacing. Using the above techniques, spectral purity of better than 10^{-11} can be obtained. For long-term reliability the output is servo-controlled to some stable reference device—Lamb dip technique, for instance. This technique reduces the frequency instability to a few parts in 10^{13}.

2.2 *Directionality*

Lasers are highly directional in that the associated beam divergence is small. In comparison, conventional sources normally emit over 4π steradians. The number of oscillating tranverse modes determines the beam divergence and spatial intensity distribution. The lowest order tranverse mode TEM_{00}, for instance, has the lowest beam divergence and a smooth gaussian intensity distribution. The lower limit to beam divergence is essentially set by diffraction. This lower limit is given approximately by the equation, $\theta = k.\lambda/d$, where d is the diameter of the aperture through which light emerges, λ the wavelength and k a numerical factor. For uniform beam $k = 1{\cdot}22$ and for gaussian $k = 2/\pi$. The beam emerging from lasers which equal or approach this minimum value is said to be diffraction-limited. Lasers operating in higher order transverse modes have larger divergence.

2.3 *Coherence*

Coherence of a source relates to correlation of phases of light waves at two points in space at a given instant of time or at two instants of time at a given point in space. Thus one talks of both spatial and temporal coherence. Laser light is both spatially and temporally coherent. Coherence is given in terms of a mutual coherence function denoted by $\Gamma_{12}(x_1, x_2; t_1, t_2)$. This quantity, which is a complex number, measures the correlation between light waves at two points P_1 and P_2 at different times t_1 and t_2. Thus the quantity $\Gamma_{12}(x_1, x_2; t_1, t_2)$ has both spatial and temporal contributions. The absolute value of $\Gamma_{12}(x_1, x_2; t_1, t_2)$ lies between 0 and 1. The value 0 corresponds to complete incoherence and 1 to completely coherent light. Lasers by far have $\Gamma_{12}(x_1, x_2; t_1, t_2) = 1$ and hence are completely coherent. A good spatial coherence implies better focusability and hence higher intensity. Temporal coherence is important in applications in which the laser beam is split into two parts which, after traversing different path lengths, are made to combine, as in interferometry.

2.4 *Brightness*

Brightness of a source is defined as the power per unit area per unit solid angle emitted by the source. Brightness of lasers in general is far higher compared to conventional thermal sources. A Hg-vapour lamp with an output of 100 watts has a brightness of 95 watts/cm^2/steradian. In comparison, a 1 milliwatt He–Ne laser has five orders of magnitude higher brightness. The same laser can also be shown to be $\sim$ 100 times brighter than the sun. Further, the electric field associated with an electromagnetic wave depends on intensity and is given by E(v/cm) $\sim 27{\cdot}5\sqrt{I}$(W/cm^2). With lasers power densities at the focus of a lens can be of the order of 10^{12} to 10^{16} W/cm^2. The corresponding field strength equals $2{\cdot}75 \times 10^7$ v/cm to $2{\cdot}75 \times 10^9$ v/cm. In comparison, the field experienced by an electron in the first Bohr orbit in the hydrogen atom is $\sim 5 \times 10^9$ v/cm. When the electric field associated with the laser becomes comparable to this cohesive field materials break down.

3. Lasers for material processing

In material processing with lasers, lasers serve as a controlled heat source. The absorption of laser light and hence temperature rise are determined by the optical and thermal properties of the material (Charschan 1972).

Optical properties of the material decide the absorption coefficient, which also depends on surface finish, reflectivity vs wavelength, temperature and state of oxidation of surface. Most metals have reflectivity in the range of 0·3 to 0·9 in the visible spectrum and $>0{\cdot}9$ for radiation beyond 5μ wavelength. The absorption of silicon, however, decreases rapidly towards longer wavelengths, with intrinsic absorption in the vicinity of 1μ.

Heat flow is dependent on both thermal conductivity and specific heat of the material concerned. In fact, the important factor in heat flow is thermal diffusivity which determines how rapidly a material will accept and conduct thermal energy. Depending on the value of thermal diffusivity, laser energy and pulse duration have to be altered to suit a given application.

The characteristics of laser that are important in material processing are: (a) its wavelength, (b) beam divergence and (c) power–time characteristics. The output wavelength of a laser is decided by the lasing transitions supported by the gain medium and any other frequency-selective elements used in the resonator. The resonator geometry and the number of transverse modes determine the beam divergence. The power–time characteristics are determined by the regime of laser operation. The typical characteristics of the high average power laser used for material processing can be summed up as:

a) Average power	~ 10, 1000 Watts
b) Beam quality	$\sim \lambda/10$ rms
c) Storage efficiency	$>10\%$
d) Extraction efficiency	$>60\%$
e) Service life	$\sim 10^{10}$ shots
f) Wavelength	many

Solid state lasers, CO_2 lasers and excimer lasers are some of the lasers used in material processing applications. We shall discuss the solid state lasers in greater depth with specific reference to high average power laser. CO_2 lasers and excimer lasers are discussed elsewhere in this volume.

4. Solid state lasers

4.1 *Solid state lasers: spectroscopy*

Optically pumped solid state lasers can be considered as a twin-component system, consisting of a 'host' wherein 'dopant ions' are embedded. The dopant ions that have been made to lase belong to one of three groups, viz. transitional metals (Cr^{3+}, Co^{2+}, Ni^{2+}), the rare earths (Nd^{3+}, Er^{3+}, Tm^{3+}, Pr^{3+}, Gd^{3+}, Eu^{3+}, Yb^{3+},

Sm^{2+}, Dy^{2+} and Tm^{2+}) or an actinide ion (U^{3+}), and are embedded in various host materials. Out of more than 100 ion–host combinations only very few, such as ruby, alexandrite, Nd:YAG, and Nd:glass have met with commercial success. In these hosts the ions exhibit sharp fluorescent lines, strong absorption bands and high quantum efficiency for the fluorescent transitions. Colour centre lasers, though solid-state in nature, are not used for material processing applications on account of their small output power, about a few milliwatts. They offer wide tunability in the near-IR region and are used in high resolution molecular spectroscopy and in studies of atmospheric pollutants. These will not be discussed here.

4.2 *Power–time characteristics*

Solid state lasers operate normally in one of the four regimes, viz. (i) free running, (ii) Q-switched, (iii) mode-locked or (iv) continuous mode (CW).

In the free-running regime, the stored energy in the amplifying medium appears as a burst of pulses with random amplitude, duration and separation. It is the integrated energy over the pulse train that is of importance here. The pulse train envelope may vary from a few hundreds of microseconds to a few milliseconds depending on the excitation pump pulse duration. The energy and pulse duration are altered to suit a given application. In the Q-switched mode, the stored energy in the amplifying medium appears as a single pulse of very short duration ($\sim$10–50 ns). Thus the peak power can be of the order of a few megawatts to tens of megawatts. Pulses as short as a few picoseconds can be had from solid state lasers by mode locking. The peak power in this case can be $\sim$100 megawatts. Pulse duration can also be varied by additional etalons within the resonator. For the continuous wave operation, Nd:YAG lasers are the best candidates. Nd:YAG lasers with continuous powers in excess of 500 watts are commercially available.

4.3 *Specific problems of high average power solid state lasers*

Solid state lasers suffer from an overall low efficiency, typically a few per cent. Broad-band pump sources used to create inversion in solid state lasers couple on an average $\sim$0·5%–2% of electrical energy as stored energy in the gain medium. Approximately 7% of the pump energy is deposited as heat in the volume of the material. The limits to high average power from solid state lasers is essentially dictated by thermal gradients set up in the gain medium due to non-uniform pump light absorption and cooling. The thermal gradient gives rise to lensing and birefringence (Koechner 1976). This thermal gradient results in degradation of the optical quality of the beam and eventually may lead to thermal fracture of the material.

Traditionally the solid state lasers are developed in the form of cylindrical rods. The pumping and cooling is through the curved cylindrical surface resulting in a radial variation of gain and temperature, as shown in figure 1. On account of the varying optical path for rays constituting the beam, the material exhibits lensing behaviour (Koechner 1970). In a cylindrical rod geometry, with radial temperature gradient and beam propagation parallel to the cylinder axis, the azimuthal and tangential component of the stress at any radial co-ordinate r is different, resulting in reduction in symmetry of the material and the normally isotropic material

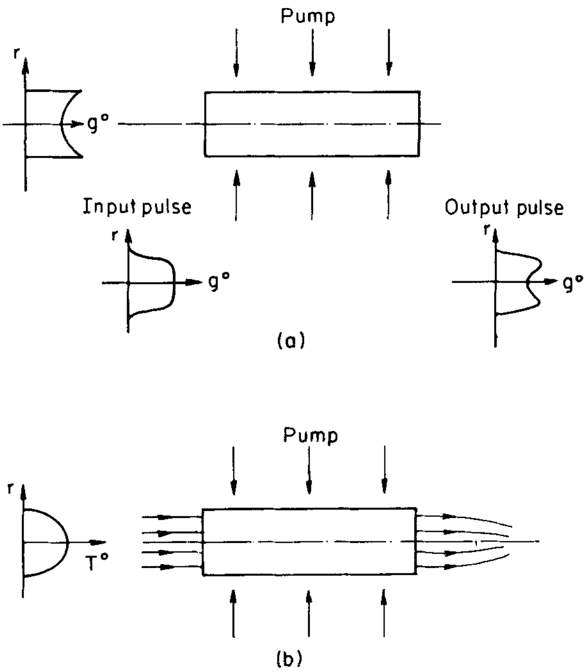

Figure 1. **a.** Gain variation in rod geometry—change in radial profile of beam. **b.** Temperature variation in rod geometry—thermal lensing.

behaves as a uniaxial or biaxial medium resulting in depolarization of the beam (Foster and Osterink 1970). Thus thermal management sets an upper limit to high average power operation for solid state lasers from conventional rod geometry.

The solution for the use of solid state lasers in high average power applications lies in (a) tailoring material composition of the host medium such that the change in optical path per unit change in temperature, dS/dT, is close to zero (athermal glass), and/or (b) configuring the laser medium and choosing the beam propagation direction such that every ray in the beam experiences the same integral of gain and phase shift along its path through the medium. This results in no amplitude or phase distortion.

Change in optical path, S, through the medium is a function of two parameters, viz. linear coefficient of expansion, α, and change of refractive index, n, with change in temperature, T, and is given by

$$dS/dT = (n-1)\alpha + dn/dT \sim 0$$

Material composition of the host medium is chosen to have a negative value for dn/dT such that the sum of the two contributions to optical path length change is close to zero. Such glasses are called 'athermal glass'. An example of such glass is LHG-8 of HOYA, Japan.

The other technique of minimizing thermal problems is by configuring the laser medium. The laser medium is configured in the form of a slab with high aspect ratio (width to thickness). The slab is pumped and cooled through the broad faces and the beam propagation direction is chosen as a zigzag path through the slab utilizing total internal reflection at the glass–coolant boundary (Chernoch and Martin 1972), or as a normal to the pumped faces—axial gradient configuration (figure 2). In the case of the slab, the temperature gradient is one-dimensional, and due to the zigzag path of the beam the integral path length for each ray in the beam is the same. Similarly, in the axial gradient configuration (figure 2) the beam propagates parallel to the temperature gradient and no thermal lensing occurs even at high input power for both the cases. Depolarization arises on account of the beam propagating through a stressed medium. However, in slab geometry, due to one-dimensional temperature gradient (along the thickness of the slab) planar stresses are developed. As the beam makes a complete zigzag through the medium, it propagates through zones of compressive and tensile stresses resulting in an averaging process. Thus the beam now sees a virtually unstrained medium introducing no depolarization of the beam. This is shown for axial gradient configuration in figure 3.

Thus the thermal problems confronting the traditional cylindrical geometry can be overcome by proper choice of material composition and configuring the laser medium (Kane *et al* 1983; Eggleston *et al* 1982). The slab geometry is thus an excellent choice for high average power applications without any compromise on beam quality.

Better beam quality and a proper choice of focusing optics renders the beam useful for a variety of processing applications.

5. Role of focusing optics

An unfocused beam on target does not produce sufficient power density to raise the temperature of most materials beyond a few hundred degrees. Hence the need for focusing optics. Theoretically, a gaussian beam can be focused with an ideal lens to

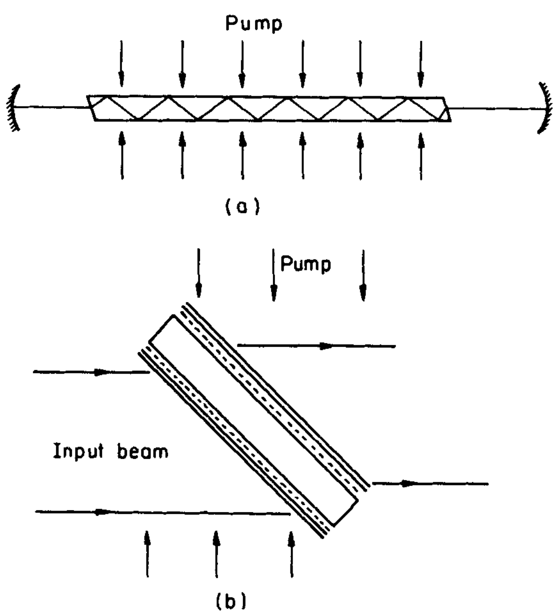

Figure 2. **a.** TIR slab geometry. **b.** Axial gradient configuration: disc amplifier geometry.

spot diameter of the order of the wavelength. A small focal area also minimizes the heat-affected zone. In order to provide the smallest focal spot, one must use a short focal length lens. A short focal length lens has a smaller depth of field, z, given by $z = (\lambda \cdot F^2/a^2) \sim (r_s^2/\lambda)$, where a is the radius of the lens, F its focal length, r_s the spot size and λ the wavelength. A small depth of focus demands more stringent control on surface finish. The inset in figure 4 provides dependence of depth of focus z on focal spot size, w_2 (r_s). Thus one must design an optical system that will provide a reasonable compromise between large depth of field and small focal length. Choice

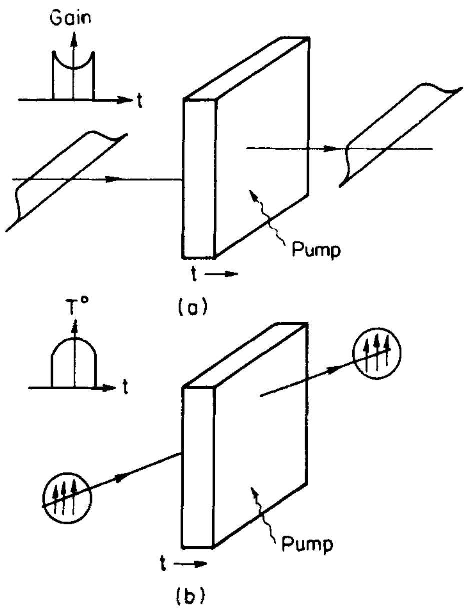

Figure 3. **a.** Gain variation in slab geometry and its effect on input beam. **b.** Polarization dependence due to one-dimensional temperature profile in disc geometry.

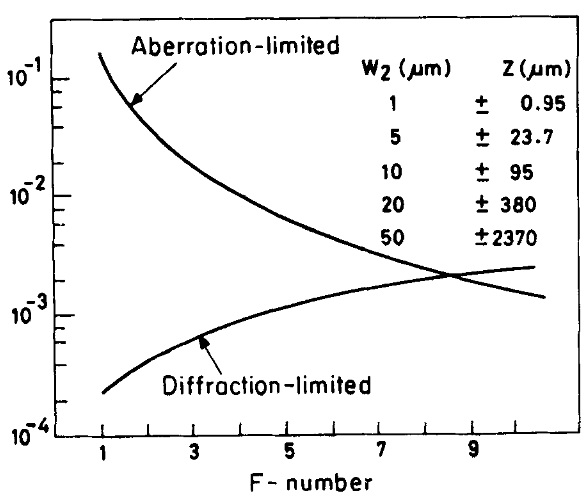

Figure 4. Focal spot size dependence on diffraction and lens aberration.

of a lens is also dictated by lens aberrations that degrade the performance of the optical system. For a monochromatic collimated laser beam, the most important aberration is the spherical aberration. Spherical aberration becomes more important for lenses with F-number smaller than 5. Figure 4 gives focal spot size dependence on F-number showing the effects of spherical aberration and diffraction.

6. Conclusion

With the new concept of using slab geometry, the solid state laser can be scaled to the high average power regime. With the additional advantage of operating at lower wavelengths, which is desirable for material processing applications (specifically for metals), the solid state laser is the first choice for this application. With narrow-band pumping sources, such as laser diodes, solid state lasers plagued by thermal management problems may become a strong contender for high average power application with overall high efficiency.

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