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A device for laser beam diffusion and homogenisation

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Abstract With the advent of methods for the pulsed annealing of materials using laser radiation, it has become increasingly important to achieve good beam uniformity. We describe a device based upon a diffusing screen coupled to a light guide which accepts a multimode beam directly from a laser and, irrespective of input beam inhomogeneities, yields an output beam with an exceptionally flat and uniform intensity distribution. The optical efficiency of the device is high and the output radiation power density can be controlled by adjusting diffuser design parameters. Deleterious speckle patterns in the output beam can be virtually eliminated.

In recent years, it has become apparent that high-power laser radiation can be used to anneal materials such as semiconductors and metals. In the former case, the principal application has been for the annealing of ion-implanted surface layers of Si and GaAs (Khaibullin *et al* 1977, Young *et al* 1978, Kachurin *et al* 1976). However, for further information on the wide range of applications now emerging, the reader is referred to Leamy and Poate (1979). The annealing techniques can be broadly classified into two groups: those which use pulsed (usually *Q*-switched) radiation in a stationary spot and those which use a scanning cw beam, although there are hybrid modes of operation. Nevertheless, in all cases the uniformity of the local annealing which is achieved depends upon the intensity distribution in the laser spot.

An unfocused laser beam can have an exceptionally non-uniform intensity distribution if multimode laser operation is employed, taking the form of a Gaussian multiplied by a Hermite polynomial. Single 00 mode operation yields reduced power output and gives a beam with a simple Gaussian envelope. Furthermore, a beam of any type can be focused through lenses on to a specimen surface, although the final main intensity distribution will again be Gaussian, generally with a number of diffraction sidebands.

Many of the major intensity variations can be removed from laser beams by passing them through diffusers of various types, such as ground-glass screens or opal-glass sheets. Some of the parameters required for optimum plate diffuser construction are discussed in general terms by Lahart and Marathay (1975). The range of angles through which light is scattered depends upon the basic structure of the diffuser plate. Ground-glass screens scatter most light into a relatively narrow cone about the incident beam direction although considerable speckle is introduced. The latter, together with any residual mode pattern, can produce damage in an irradiated specimen which is placed close to such a screen. If the specimen is moved away from the screen, the available beam power density drops rapidly due to the diverging radiation pattern.

Many of the undesirable features of the conventional system just described can be eliminated by use of a diffuser/light guide system of the type shown in figure 1 (Cullis *et al* 1978). This device is particularly effective in eliminating inhomogeneities from high-power multimode beams which, of course, exhibit poor initial coherence. The laser output is directed on to the input face of the guide which, in this case, is flat and has a surface finish imparted by grinding with 14 μm diamond powder held on a hard lapping plate. As the beam enters the light guide it is, therefore, fairly strongly diffused, although microscopic intensity inhomogeneities remain. Most of the incident light is scattered close to the forward direction and passes down the guide being subsequently contained by total internal reflection at the guide wall. A relatively small proportion of the incident light is scattered through large angles at the input face and is lost. As the radiation propagates down the guide, repeated internal reflection further diffuses the beam and speckle components are progressively eliminated. This process is enhanced, especially for near-axis light, by introducing a curve into the guide. A bend of approximately 90° has been found to be particularly effective in suppressing any remaining speckle while giving rise to minimal light losses. However, such bends introduce caustic patterns into the transmitted light (Kapany 1957) and a further length of guide is required to rehomogenise the beam. In this section we introduce a taper to constrict the guide and so obtain an increased beam power density. The light finally emerges from the guide through an exit face which is normal to the guide axis and highly polished. It is often convenient to use a circular guide exit, although other geometrical forms (with straight edges) can be employed.

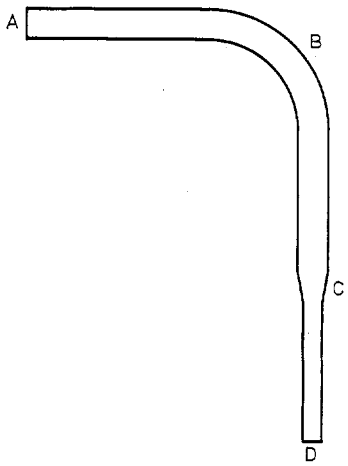

Figure 1 Light guide diffuser with ground input face A, curved section B, tapered section C and polished output face D.

The light guide itself can be fabricated from a variety of transparent glasses. However, silica has been found to be particularly suitable, having a refractive index of 1·46 and a transmission range of 0·19–3·5 μm. The latter permits use of the silica guide diffuser with most common lasers operating in the visible or near-infrared regions of the spectrum. The diameter of the input end of the guide should be matched to the laser beam diameter for efficient beam homogenisation. The input diffusing element can take the form of thin opal-glass or a similar plate. However, light-scattering angles are generally greater than for a ground surface and larger power losses are incurred. During diffusion in the guide considerable beam divergence is introduced and the residual coherence of the light degraded. Therefore, in normal operation, for greatest annealing uniformity specimens should be placed close to the exit face (within about ½ mm). Larger spacings give a reduced

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light intensity at the edge of the output beam. The final spot can, of course, be projected on to a remote specimen by use of a suitable lens system. However, due to the widely diverging radiation, an especially large lens aperture and short lens focal length are required to minimise power losses and to maintain optimum intensity uniformity. Such a projection system would permit the spot position to be scanned with appropriate deflection mirrors over a specimen surface.

The final power density delivered by the guide can be increased by decreasing the final diameter of the guide after the taper. The length of the latter guide section should not be too great since leakage of skew rays from the guide (Snyder and Mitchell 1974) promotes a build-up of intensity on the guide axis and so degrades the flat beam profile. It is also important to maintain the guide output face in a clean, polished condition since optical imperfections can significantly degrade the uniformity of the light distribution.

By use of the guide diffuser described above it is possible to homogenise a multimode beam of the type shown in figure 2A to give a circular, uniform distribution as in figure 2B. This particular example pertains to a *Q*-switched ruby laser beam with initial and final diameters of about 10 and 6 mm respectively. Only approximately 40% of the incident light was lost during transmission through the guide and the reduction in final spot diameter ensured that an increased final power density was available. Figure 3 shows intensity distributions derived from microdensitometer traces taken across images of initial and diffused spots recorded on photographic film. It is clear that the initial mode pattern intensity non-uniformities are removed in the final diffused spot which has a flat-topped profile. An examination of such traces, together with estimates obtained from observations of the threshold for annealing of amorphous, ion-implanted Si, indicates that residual relative intensity variations in the diffused spot are less than about 10% in magnitude.

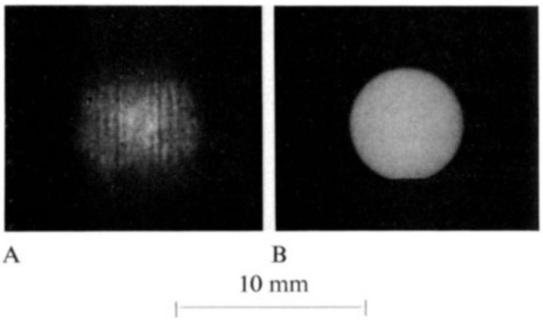

Figure 2 Beam spots obtained from a *Q*-switched ruby laser (pulse length 30 ns): A, multimode pattern obtained directly from laser; B, homogeneous spot obtained using guide diffuser.

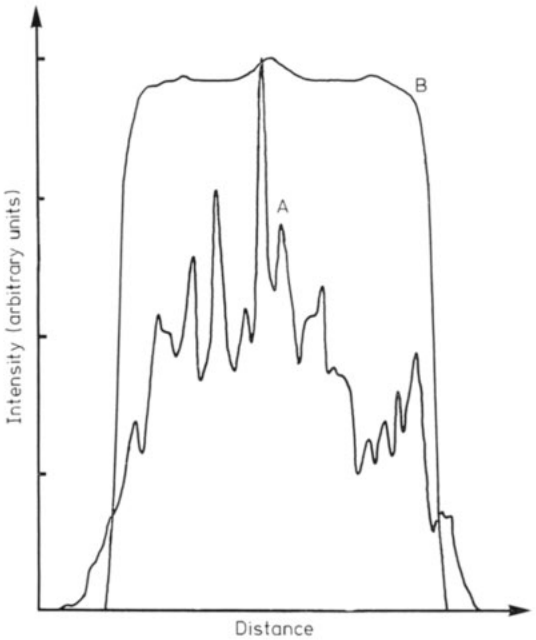

Figure 3 Intensity profiles across the diameters of an initial multimode spot (A) and a diffused spot (B).

Such diffused laser beams can be used to anneal ion-implanted Si with radiation power densities of greater than 100 MW cm^{-2}. The exceptionally uniform electrical activation of implanted dopant species obtained is likely to prove most useful for electronic device fabrication. In addition, for laser annealing through surface SiO_2 layers, substantial beam uniformity is an advantage due to the relatively low SiO_2 damage threshold. Good beam uniformity is also particularly important for the laser annealing of semiconductors with volatile constituents, such as the III–V compounds. In this case, unintentional excessive heating of localised areas can promote damage by enhancing loss of the group V component. This can be avoided (Cullis *et al* 1979) by using an homogenised laser beam produced by a guide diffuser of the type described in the present article.

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