Beam-splitter mount for efficient monitoring of mode-locked and synchronously pumped cw lasers

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Monitoring the optical pulses from mode-locked and synchronously pumped continuous wave (cw) lasers, reference beams are taken from the main beams with beam splitters. Depending on the angle with respect to the incident beam and the direction of the rotation axis of the beam splitter, light fractions of different polarizations can be selected. Based on practical and theoretical considerations an alternative beam-splitter mount has been designed which efficiently utilizes the available optical power.

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INTRODUCTION

When a ray of light impinges on a boundary surface of two substances with different indices of refraction, part of the ray is refracted and another part is reflected. Because of the *equation of continuity*,[1] the projections of the resultant electric and magnetic field vectors in the plane of the boundary surface have to be the same at both sides of the surface. This results in a partition of the intensity between refracted and reflected light rays, depending on the angle of incidence and the polarization conditions of the incident beam.

The following relationships are valid for the transparent media: $\mu = \mu_0 (\simeq 1)$ and $\sqrt{\epsilon} = n\sqrt{\epsilon_0}$ (μ = permeability, ϵ = permittivity, subscript 0 denotes values in vacuum, n = refractive index). Then from *Fresnel's formulae*,[1] one can calculate the relative intensity of the reflected and refracted fraction of light as a function of the angle of incidence of the primary ray at given conditions for refractive indices and polarization direction. In Fig. 1 the curves are given for the percentages of reflected light as a function of the angle of incidence α_e at an air–glass transition for unpolarized (natural) light (R_{eo}) and light plane polarized with the electric vector in a direction perpendicular ($Re_\perp$) and parallel ($Re_\parallel$) to the plane of the incidence (in this case $n_i = 1.523$). The curves were calculated with the following relationships:

$$Re_\perp = \frac{\sin^2(\alpha_e - \alpha_i)}{\sin^2(\alpha_e + \alpha_i)},$$

$$Re_\parallel = \frac{\tan^2(\alpha_e - \alpha_i)}{\tan^2(\alpha_e + \alpha_i)},$$

$$R_{eo} = \frac{R_{e\parallel} + R_{e\perp}}{2},$$

where α_e is the external angle of incidence, α_i the internal angle of refraction, and $\sin \alpha_i n_i = \sin \alpha_e n_e$. The lower angle scale α_i shows the angles of refraction corresponding to the angles of incidence α_e on the upper scale. Figure 2 shows the same curves but now for a glass–air transition. With α_i and α_e interchanged the same relationships are valid for the internal reflections

$$Ri_\perp = \frac{\sin^2(\alpha_i - \alpha_e)}{\sin^2(\alpha_i + \alpha_e)},$$

$$Ri_\parallel = \frac{\tan^2(\alpha_i - \alpha_e)}{\tan^2(\alpha_i + \alpha_e)},$$

$$R_{io} = \frac{R_{i\parallel} + R_{i\perp}}{2}.$$

Now α_i is the internal angle of incidence and α_e the external angle of refraction.

I. PRACTICAL CONSIDERATIONS

When employing laser radiation, part of the light is used for monitoring purposes. In some spectroscopic appli-

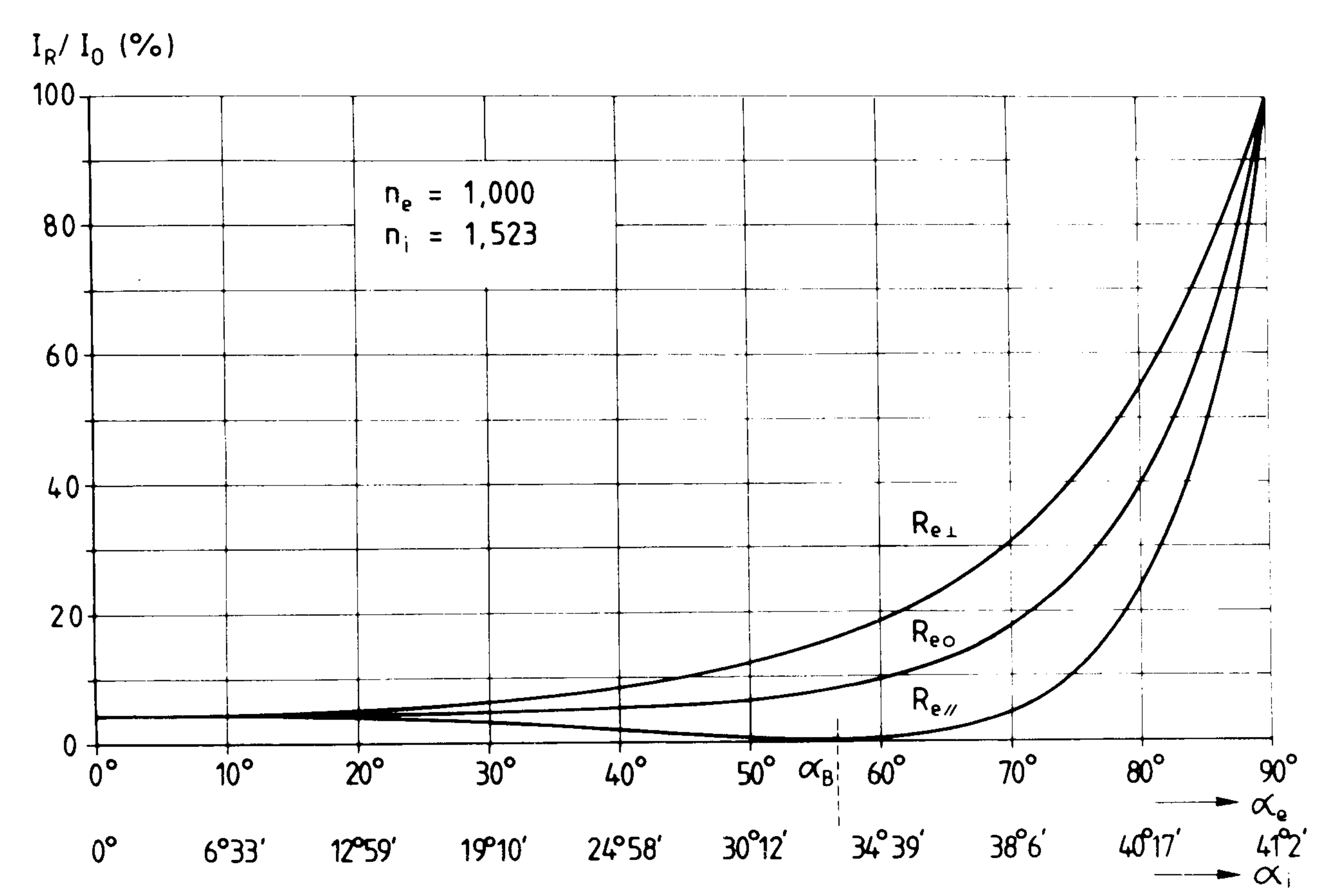


FIG. 1. Reflected fractions of light on the boundary surface of an *air–glass* transition for unpolarized light (R_{eo}), and light plane polarized with the electric vector parallel ($R_{e\parallel}$) and perpendicular ($R_{e\perp}$) to the plane of incidence. α_B is the Brewster angle (56°43').

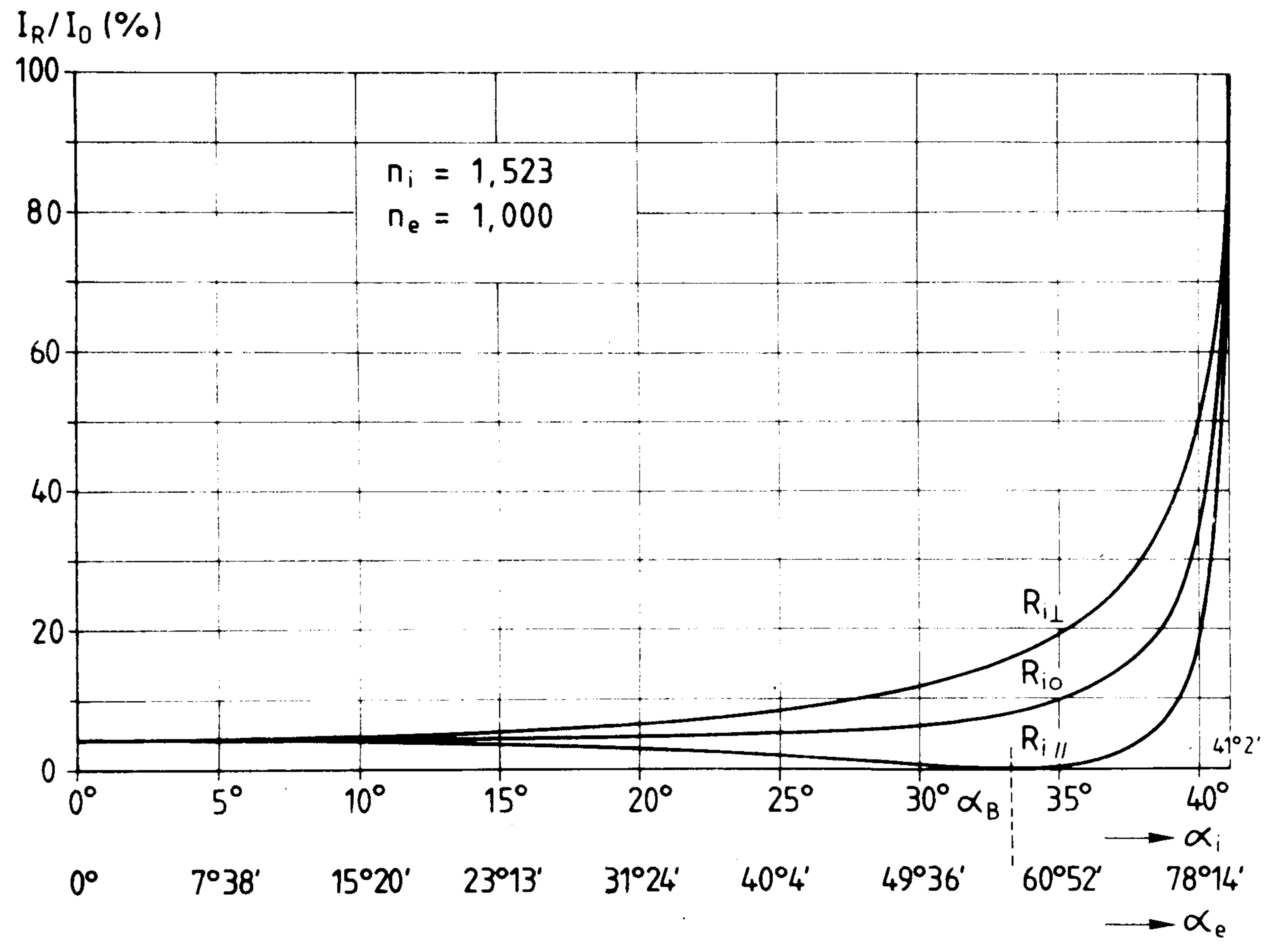


FIG. 2. Reflected fractions of light on the boundary surface of a *glass–air* transition for unpolarized light (R_{io}), and light plane polarized with the electric vector parallel ($R_{i\parallel}$) and perpendicular ($R_{i\perp}$) to the plane of incidence. α_B is the Brewster angle (33°17′).

cations all available power is desired and light for monitoring can hardly be traded off, especially when a dye laser is synchronously pumped or (and) the power is used in a frequency doubling setup (note that the output power is then exponentially dependent on the input power), as much power as possible with the given laser has to be generated. Another reason for the use of a small amount of power for monitoring is that mode locking can be achieved, more easily with less optical power in the cavity.

With commercial ion lasers and dye lasers for continuous-wave operation, like the CR 18 UV and CR 590 from Coherent Radiation, the output beam is plane polarized with an extinction ratio of at least 100:1 with the electric vector vertical. When these lasers are mode locked or synchronously pumped, a reference beam is split off for monitoring the optical pulses (100 and 4 ps full-width at half-maximum[2,3]) with fast photodiodes.[4] Normally a thin uncoated mirror substrate[5] is used as a beam splitter, with an angle of about 45° to the beam, rotated along a vertical axis.[6]

In this way the front surface of the beam splitter deflects about 8% towards the monitor, the light being almost totally vertically polarized (see Figs. 1 and 2). The back surface also deflects about 8%.

The fast photodiodes are connected to the sampling heads of a sampling oscilloscope (e.g., Hewlett–Packard 1430 C or Tektronix S4, S6; rise time some tens of picoseconds). The dynamic range of such a sampling head is in the order of a few volts; overload blows up the sampling diodes. Normally we use peak voltages at the input of a few hundreds of mV maximum. To get such a response out of the fast photodiodes some mW's average mode-locked power (AMLP) are necessary, depending on the wavelength and the type of photodiode (avalanche, PIN[4]). When the argon-ion laser is mode locked for fluorescence decay or anisotropy measurements,[7–9] the output power of the laser is between 100 and 200 mW (AMLP). When synchronously pumping the dye laser,[2,3,10] the ion laser delivers output power in the range of several watts, the dye laser hundreds of mW's (AMLP). Thus, when using the 16% beam splitter as described above, density filters with transmissions in the range of 0.1%–1% have to be used to attenuate the monitor beam. Of course this is a clear waste of laser intensity.

II. IMPROVED EFFICIENCY SETUP

Referring to Figs. 1 and 2, it seems inviting to rotate the beam splitter around a horizontal axis in order to split off a much smaller amount of light from the main beam for monitoring. The problem then is that the amount of horizontally polarized light in the monitor beam becomes relatively large. It is not really known how this affects, for instance, the measurements of pulse width and after pulse.

From the theory of mode-locking cw lasers,[10–12] it is not directly apparent what the contributions are of perpendicularly polarized light. A closer look at the mode-locking device in our argon-ion laser (a Brewster cut, acousto-optic modulator) and the mode-locking mechanism in the synchronously pumped dye laser does not give any reason to suppose differences in mode-lock action for different polarized fractions of light.

We have built a beam-splitting device with an uncoated optical substrate that can be rotated around a horizontal axis (Fig. 3). The angle between the surface(s) and the beam can be adjusted by rotating the yoke to control the percentage of power in the split-off beam. The optical substrate is pressed onto the yoke with simple metal clips. A mirror, mounted above the rotation axis with double sided coated adhesive tape, is used to get the monitor beam in a more or less horizontal direction. Then another mirror mount (NRC, model MM2) is used to deflect the monitor beam towards the photodiode.

III. RESULTS AND DISCUSSION

We have compared the pulse shapes on the display of the sampling oscilloscope from monitor beams obtained at two significantly different orientations of the optical substrate. Figure 4(a) shows the pulse shape of our linearly polarized mode-locked Ar-ion laser at 514.5 nm operating with an extinction ratio of approximately 200:1. The beam is reflected off of an optical substrate rotated by 45°, with the rotation axis in the vertical plain, perpendicular to the main beam. A 1:100 neutral density filter was used to attenuate the monitor beam.

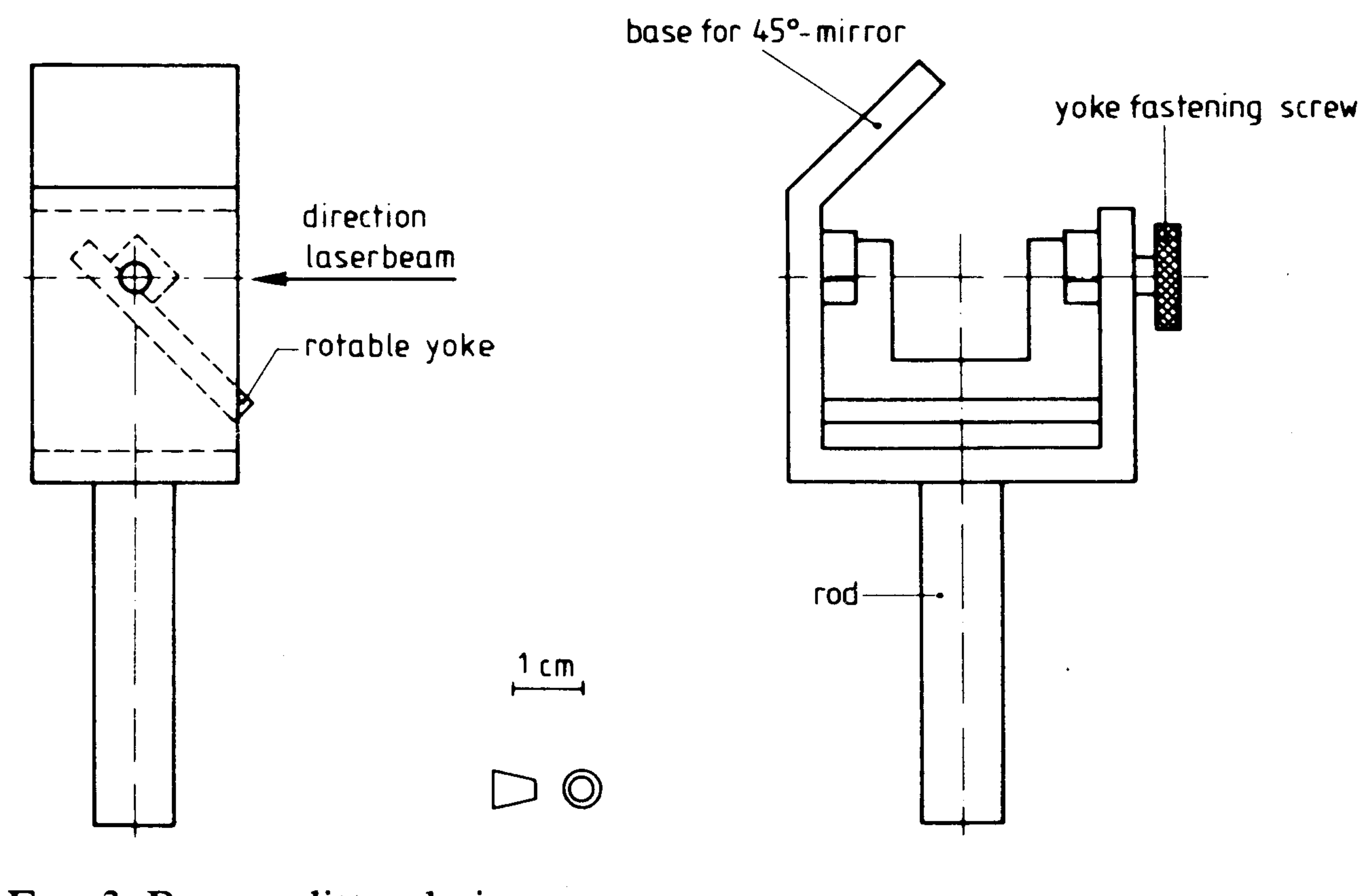
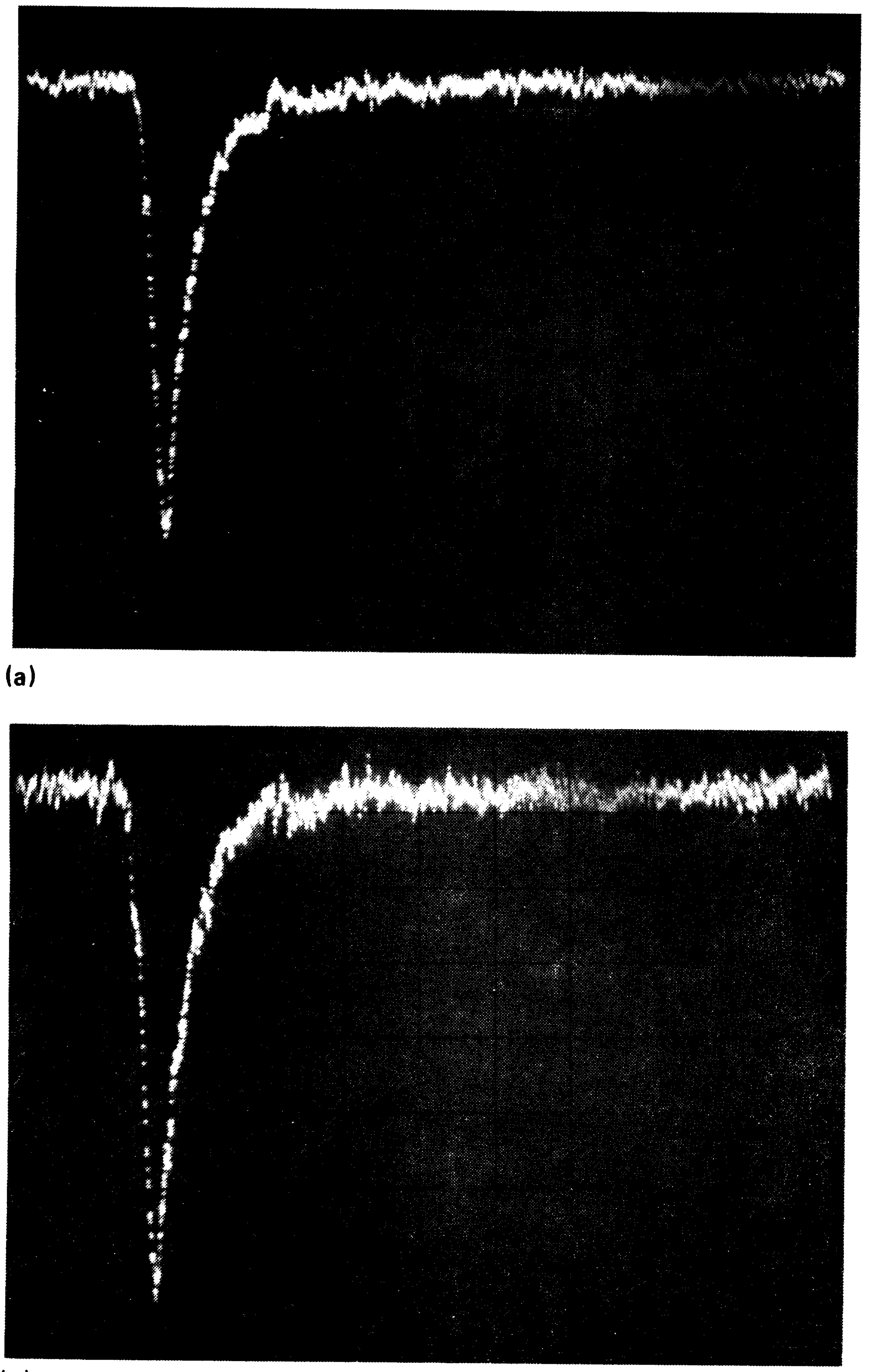


FIG. 3. Beam-splitter design.



(a)

(b)

FIG. 4. Pulse shapes on the display of a sampling oscilloscope from the output (514.5 nm) of a mode-locked Ar-ion laser, detected with Telefunken BPW 28 photodiodes in a home-built mount. The optical substrates were rotated 45° around a vertical axis (a) and about 57° around a horizontal axis (b).

Figure 4(b) shows the pulse shape of the same laser output reflected off of an optical substrate, rotated by approximately 57° (see Figs. 1 and 2), with the rotation axis in the horizontal plane, perpendicular to the main beam. No density filters were necessary. In this way, primarily a horizontally polarized fraction was selected out of the principally vertically polarized main beam. When measuring the output power of the laser there is hardly any decrease in power meter deflection (Coherent Radiation model 201), when our beam splitter is placed in between.

Observing the pulse shapes on the display of the sampling oscilloscope, we could not discover any change in pulse shape (width or presence of after pulse) with the two ways of mounting the beam splitter. Of course there is a small but continual variation in the pulse shape, caused by jitter of the optical pulse with respect to the trigger signal from the mode-locker driver. In our case this jitter is mainly caused by pressure instabilities of the water supply cooling the laser head.

Another effect, corrected earlier, had reduced the degree of polarization of the output beam of the argon-ion laser to much below the specified 100:1. It turned out that the substrate of the beam splitter, which deflects a small amount of light for the light regulator of the laser, was birefringent. This birefringence was caused by the hardening of the cement, fastening the substrate to the holder, over a period of several years.

Since the degree of polarization of our Rhodamine 6G dye laser[10] was significantly higher than that of the Ar-ion laser and because the power in the dye laser is relatively low, we had to rotate the beam splitter away from the Brewster angle to obtain the optimum angle for monitoring. In this configuration we were sampling, primarily, the vertically polarized laser radiation field. Since this is also the component monitored by the standard technique no significant difference in the pulse shape would be expected. In fact no difference in the shape of the dye laser pulses was detected for the two ways of mounting the beam splitter. Now the beam splitter is routinely used in its most efficient position. When the power of the monitor beam is somewhat too low, focusing with a simple thin lens is appropriate. This also improves the time response of the photodiode in some cases.[14] Focusing is, in particular, useful in the blue and ultraviolet region, where the photodiodes are less sensitive. Of course, then a fused silica optical substrate is used. When the power is still too low, an angle, somewhat different from the Brewster angle, can be chosen.

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