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# MEASUREMENT PROCEDURES FOR THE OPTICAL BEAM SPLITTER ATTENUATION DEVICE BA-1



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# MEASUREMENT PROCEDURES FOR THE OPTICAL BEAM SPLITTER ATTENUATION DEVICE BA-1

B.L. Danielson

Measurement procedures are described for the step attenuation of laser beams up to 44 dB using a specially constructed attenuator box (BA-1). With the use of an additional preattenuator beam splitter, the attenuation range can be extended to over 70 dB. The BA-1 system is designed for use at .6328 μm, .5145 μm, and 1.06 μm. The attenuation ratios of these wavelengths are calculated values. An analysis of the estimated uncertainties is also given.

Key words: Attenuation; laser attenuation; optical beam splitter.

## 1. INTRODUCTION

This manual describes some procedures for the attenuation of laser beams to low power levels with equipment designed and constructed at the National Bureau of Standards (NBS) for this purpose. This equipment consists of a seven port attenuator box, denoted by BA-1 (for beam splitter attenuator, model (1)), a preattenuator beam splitter to extend the attenuation range, and some neutral density filters. For all three of these components, the attenuation has been specified at the following wavelengths: 1.06 μm, .6328 μm, and .5145 μm. The BA-1 device produces step attenuation of a laser beam to a maximum of about 44 dB. With the preattenuator beam splitter, denoted by S1, this range can be extended as much as another 30 dB. The various low level beams generated by BA-1 can be used for detector responsivity and linearity checks. This can be done in a configuration which allows simultaneous comparison with a calibrated power meter.

The stated attenuation ratios for BA-1 are theoretically determined from a computer program based on Fresnel's equations. Many experiments were performed to establish the validity of this program. The results of the experiments were always within the experimental errors of the measurements. Since the experimental uncertainties in our case were relatively large, we have stated only the theoretical values. These results should apply to any attenuation system similar to BA-1 which uses quartz beam splitters.

The layout of BA-1 is particularly well suited for use with absorption filters for fine tuning the attenuation. However, the filters must be calibrated experimentally at each wavelength used. The errors associated with

Table I. BA-1 attenuation ratios for unpolarized radiation.

(This table should be used if laser polarization is unknown.)

| Beam Ratio Relative to m=0 Beam | 1.0 μm | .6328 μm | .5145 μm | Total Max. Estimated Uncertainty[(a)] % |
|---|---|---|---|---|
| (m=0)/(m=-1) | 27.72 | 26.96 | 26.50 | 3.5 |
| (m=0)/(m=+1) | 29.68 | 28.91 | 28.45 | 1.5 |
| (m=0)/(m=2) | 881.1 | 835.6 | 809.2 | 1.9 |
| (m=0)/(m=3) | 26,170 | 24,150 | 23,020 | 2.5 |
| (m=0)/(IN) | .9388 | .9320 | .9309 | |

[(a)] See section 6.1 for a discussion of these uncertainties.

this calibration are large, as is demonstrated here with a set of glass neutral density filters. We therefore do not recommend the use of filters in applications where the highest accuracy is required.

By way of introduction to the measurement procedures, the theory underlying the BA-1 device is given along with suggested alignment and cleaning instructions.

## 2. THEORY OF THE BA-1 ATTENUATOR

Details on the theory and use of wedged beam splitters and glass neutral density filters are given in separate publications [1,2].[1] Here we will refer only to the salient points relevant to the BA-1 device.

The heart of the BA-1 attenuator is a supersmooth quartz beam splitter[2] wedged at an angle of 2° and oriented at an angle of incident of -8.71° as

---

[1]Figures in brackets indicate the literature references at the end of this paper.

[2]The beam splitters used in this work had the following specifications: optical quality fused silica, surface figure λ/4 at .6328 μm, wedge 2.00 ± .10 degrees, and smooth to 2 nm rms surface finish. The beam splitters in BA-1 and SI are identical.

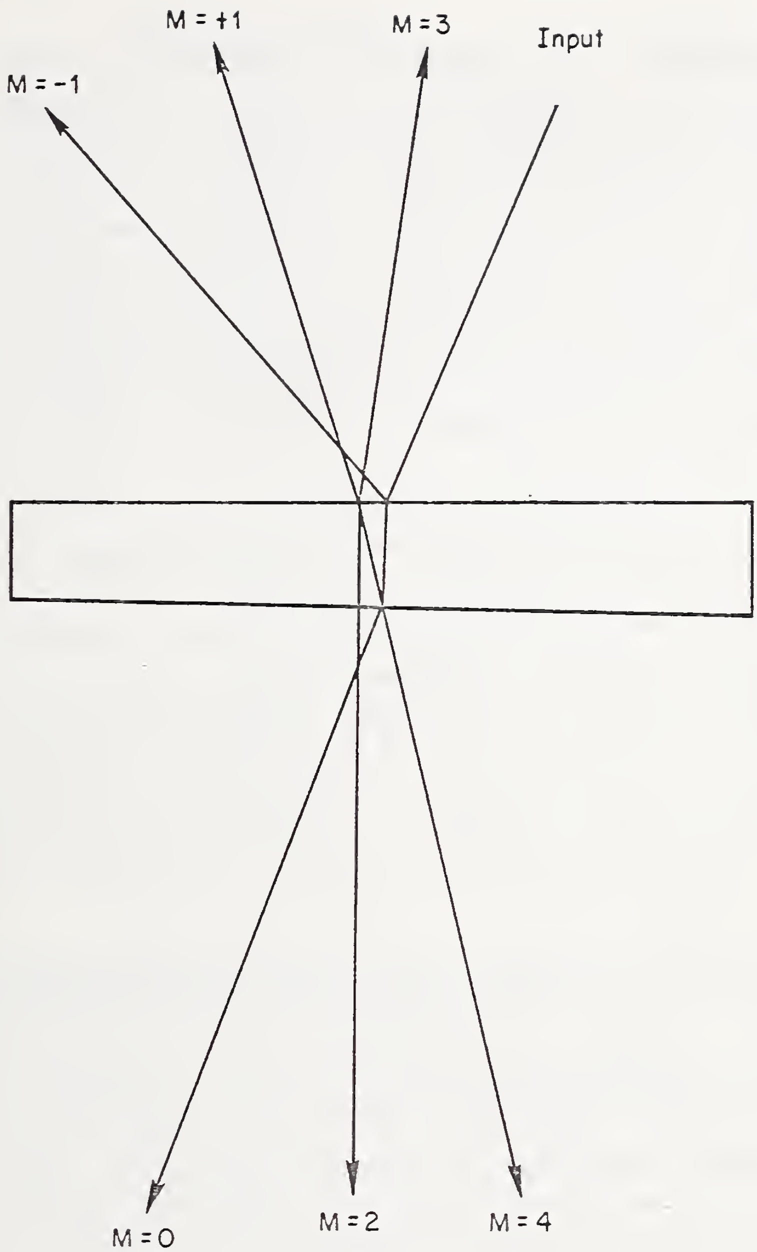


Figure 1. Path of a laser beam in the BA-1 wedged beam splitter

illustrated in figure 1. This angle of incidence is chosen so that the emerging beams are separated by angles which are approximately equal. Each time the incident beam undergoes a reflection at a surface of the beam splitter, it is attenuated by a factor of about 30 (14.7 dB). The exact ratios are given in table I. The various emerging beams are identified in the text (and on the BA-1 box) by the order number which represents the number of reflections the incident beam has undergone in the beam splitter. It will be noticed from figure 1 that there are two beams (the +1 and -1) associated with one reflection. The plus and minus signs are arbitrarily assigned to the reflections off the back and front of the beam splitter respectively.

The BA-1 box is constructed so that absorbing glass neutral density filters can be put in any of the low level attenuated beams without disturbing the alignment. The measured attenuations of these filters are listed in table II. The ports are located in the box so that if the input beam, the m = 0 beam, and one reflected beam (e.g., m = -1) are centered in their respective ports then the other less intense beams will automatically be aligned in their assigned ports. This alignment is dictated not only by reason of convenience in locating the various attenuated beams but also by the fact that attenuation ratios are a function of angle of incidence on the beam splitter. The low level attenuated beams may be used at any convenient distance from the ports.

The beam splitters are used as attenuators at high intensity levels. There is negligible absorption in quartz at the calibrated wavelengths. Damage thresholds in excess of 10 $GW/cm^2$ have been reported [3]. At very low power levels, the wedged beam splitter is less satisfactory due to alignment difficulties. The glass neutral density filters complement the beam splitters since they can be inserted into low power beams without disturbing alignment but cannot be used at high intensity levels (greater than a few tens of $mW/cm^2$) without changing their attenuation characteristics.

It should be noted that a neutral density filter should not be used in any configuration where a surface reflection could affect measurements on a less intense beam. That is, the filter should be inserted only in the lowest power beam used.

## 3. MEASUREMENT PROCEDURES

Before considering the details of measurement techniques, a general overview of our measurement philosophy may be in order. We wish to generate low level beams of known power from a laser (cw or repetitively pulsed) which can emit up to a few watts of average power. For high output powers

Table II. Attenuation ratios of neutral density filters.[a]

| Nominal Density | Measured Density 1.06 μm | .6328 μm | .5145 μm | Total Max. Estimated Uncertainty[b] % |
|---|---|---|---|---|
| .2 | .424 | .221 | .208 | 14.6 |
| .3 | .630 | .331 | .317 | 15.0 |
| .4 | .849 | .435 | .417 | 10.6 |
| .5 | .738 | .526 | .520 | 11.0 |
| .6 | .674 | .611 | .628 | (c) |
| .7 | .999 | .896 | .922 | (c) |
| .8 | .899 | .804 | .825 | 21.5 |
| .9 | 1.02 | .921 | .941 | (c) |
| 1.0 | 1.10 | .995 | 1.02 | 21.0 |
| 2.0 | 1.32 | 1.87 | 1.98 | 20.7 |
| 3.0 | 1.96 | 2.89 | 3.06 | 20.5 |

(a) Note the measured values differ significantly from the nominal values. For example, at 1.06 μm the density of the nominal .4 is greater than the nominal .6.

(b) See section 6.2 for a discussion of these uncertainties.

(c) The attenuation uniformity of these filters was not measured.

like this it is usually desirable to preattenuate this output to a few milliwatts or so. The power or energy measurements are then made at this reduced level with a suitable detector of known response. This preattenuation avoids excessive heating or damage to the detector, or filters if used, which could adversely affect measurement accuracy. Further attenuation of a known amount is made with the higher order reflections from the BA-1 box. We monitor the power on one of the output beams (usually m = 0) at a convenient level of a few milliwatts, and from the tabulated attenuation ratio we calculate the power in the other less intense beams. If desired, additional attenuation can be made with the insertion of the calibrated neutral density filters provided. The attenuated beams can then be used for determining the responsivity and linearity of sensitive detectors.

The calibrated detector may be either a power meter or a calorimeter. A calorimeter is basically an energy measuring device, and to infer average power a gated beam is required; that is, the energy is injected into the calorimeter for a known period of time. The NBS standards of laser power and energy are calorimeters [4], and generally these devices are capable of greater accuracy than power meters. However, they require additional equipment and detailed data analysis [5]. We will assume here that only a calibrated power meter is available for use with the BA-1 attenuator system.

### 3.1 Attenuation to Low Power Levels

Generation of low power level beams may be accomplished by an experimental arrangement similar to that illustrated in figure 2. This configuration provides step attenuations relative to the m = 0 beam, as given in table I. For intermediate attenuations, neutral density filters may be inserted in any of these beams (at the cost of some additional uncertainty). For high power lasers, and particularly high power YAG lasers, the arrangement of figure 3 may be more suitable. The function of the mixer S2 and mirrors M1, M2, and M3 is described in detail in section 4 on alignment procedures. For attenuation ratios up to about 60 dB the optional beam splitter S1 may be removed and mirror M1 made totally reflecting. To reduce the power entering the BA-1 box, the m = 2 beam of S1 may be used for an attenuation of about 30 dB. Alternatively, mirror M1 may be replaced by S1 and the m = -1 reflection used for about 15 dB of attenuation. The choice of configurations will depend on output power of the YAG laser and desired final power levels. Ordinarily, it is not necessary to know the exact amount of preattenuation produced by S1 since the power will be measured downstream from this point. Nevertheless, for reference a typical set of S1 beam splitter ratios (for $-5^{\circ}$ angle of incidence) is given in table III.

Table III. S-1 beam splitter attenuation ratios. Angle of incidence -5°, wedge angle 2°, fused silica.[a]

| Beam Ratio Relative to Incident Beam | 1.06 μm | .6328 μm | .5145 μm |
|---|---|---|---|
| (IN)/(m=0) | 1.071 | 1.073 | 1.074 |
| (IN)/(m=-1) | 29.68 | 28.91 | 28.44 |
| (IN)/(m=+1) | 31.79 | 31.01 | 30.55 |
| (IN)/(m=2) | 943.5 | 896.4 | 869.1 |
| (IN)/(m=3) | 28,010 | 25,910 | 24,720 |

[a] The uncertainties in the beam ratios are approximately the same as given in table I.

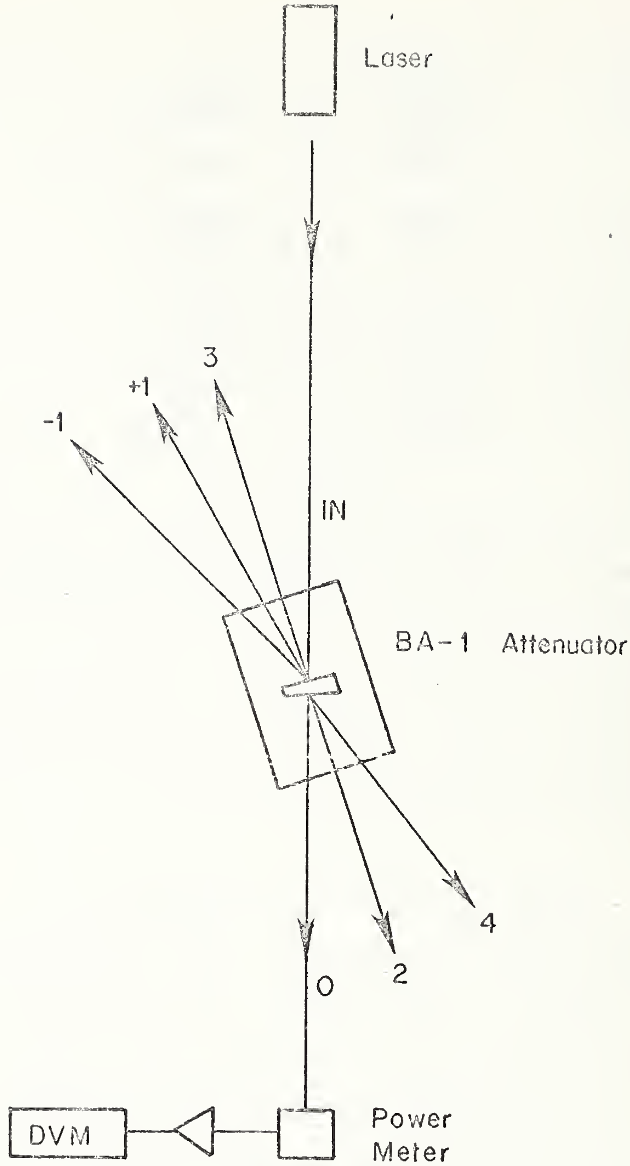


Figure 2. Layout for BA-1 attenuator

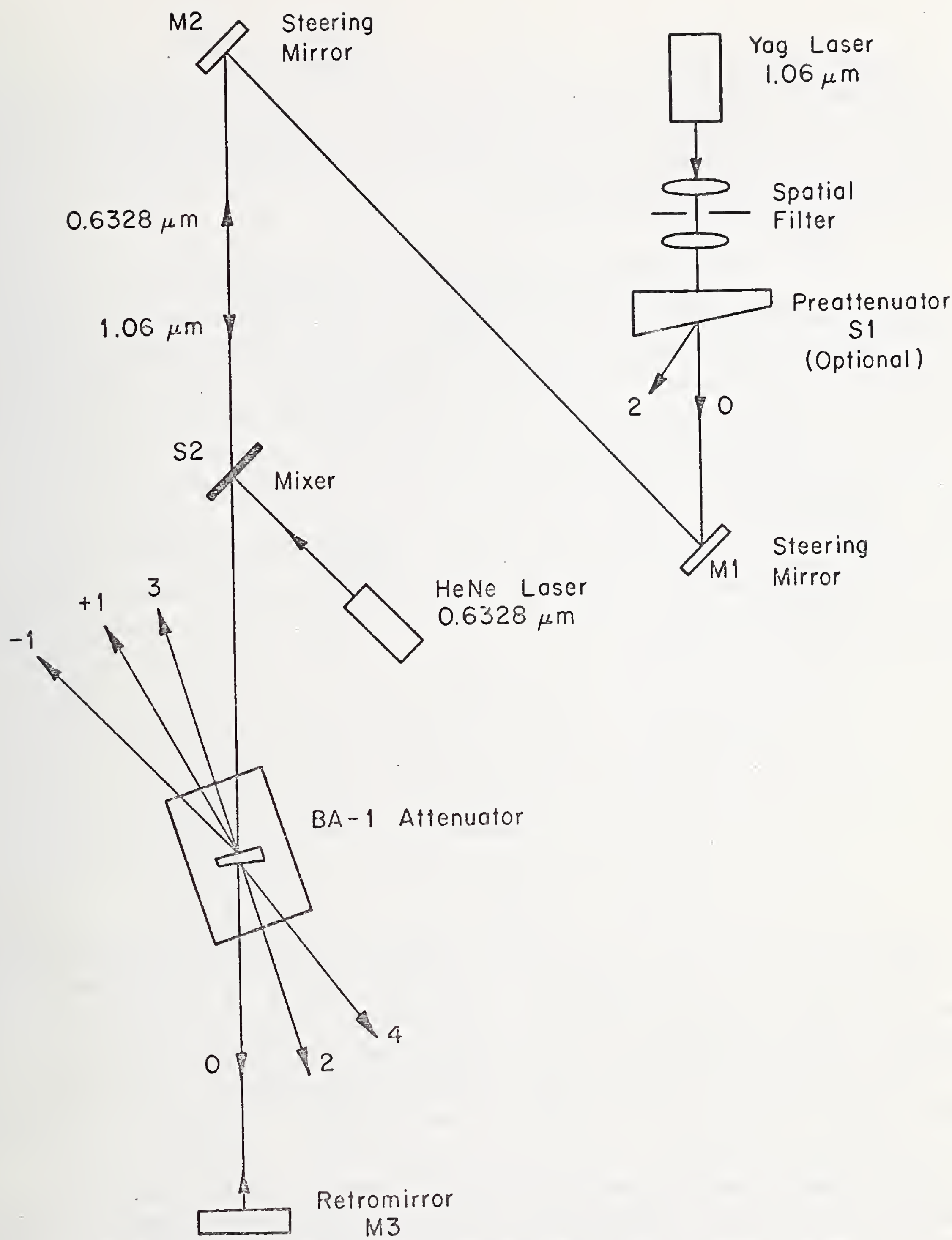


Figure 3. Layout for attenuation of a YAG laser beam to low levels with the BA-1 attenuator

After the BA-1 box is aligned (see section 4) with the incoming laser beam, we can make detector linearity checks and cw responsivity determinations at a number of power (or energy) levels. A specific example is illustrated in the following section.

### 3.2 A Specific Example of Attenuation

Let us assume we have a cw YAG laser with an output power of 20 W and that we wish to produce an attenuated beam of about 10 μW for the purpose of measuring the responsivity of a detector at this level. This requires approximately 63 dB of attenuation. To accomplish this we set up the BA-1 box with the S1 beam splitter preattenuator as shown in figure 4. Table III indicates that the m = 2 beam emerging from S1 will be attenuated by a factor of 944 (30 dB). After undergoing losses in M1, M2, and S2 we can expect about 10 mW input into the BA-1 box. This is a convenient level. The power $P_o$ is monitored on the m = 0 beam, and all other power levels are determined relative to this reading. The power $P_m$ in the mth order beam is found from table I as follows:

$$P_{-1} = P_o/27.72 = [3.606 \times 10^{-2} \pm 1.3 \times 10^{-3}]P_o$$

$$P_{+1} = P_o/29.68 = [3.369 \times 10^{-2} \pm 5.1 \times 10^{-4}]P_o$$

$$P_2 = P_o/881.1 = [1.135 \times 10^{-3} \pm 2.2 \times 10^{-5}]P_o$$

$$P_3 = P_o/26{,}170 = [3.825 \times 10^{-5} \pm 9.6 \times 10^{-7}]P_o$$

The output from port 2 (m = 2) will give about the desired power level with $P_o$ = 10 mW. Linearity of response of the detector can be ascertained by use of neutral density filters and other output beams to provide finer steps of attenuation. The calibrated filter attenuations are given in table II.

Large attenuation ratios, such as those illustrated in this example, require proper precautions to avoid scattered light. In figure 4 a baffle and light traps are shown, which help in this regard. All unused higher order beams from S1 and S2 must be suitably blocked. It also helps to physically separate the components to take advantage of the inverse square law of scattering. The power meter should be placed at least a meter behind BA-1 and tilted a few degrees so that the specular component is not reflected back into BA-1.

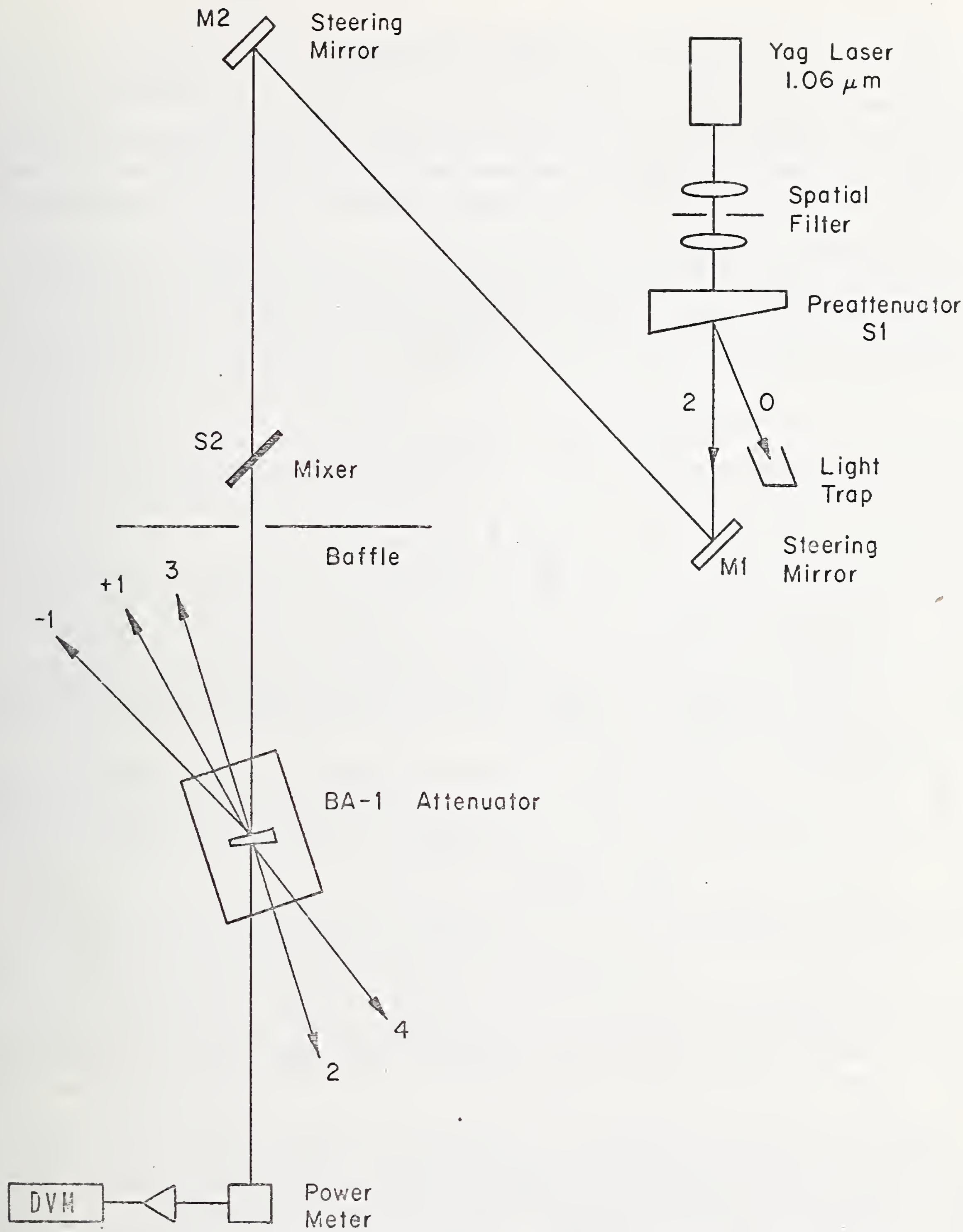


Figure 4. Example of attenuation

## 4. ALIGNMENT PROCEDURES

Alignment of the BA-1 attenuator system in figure 2 at visible wavelengths is not difficult. As mentioned previously, if the input beam, the m = 0 beam, and the m = -1 beam are centered in their ports on the BA-1 box, then the system is aligned. This can also be done at 1.06 μm, but requires care at low power levels.

One of the main concerns in the design of the BA-1 optical system was to produce a device which could be aligned easily at low infrared (ir) intensities. The easiest method of locating all the beams entering and emerging from BA-1 is to make the ir beam collinear with a visible red beam from a nominal 2 mW HeNe alignment laser. This is not essential as long as the attenuated beams are sufficiently intense to be seen by an ir viewer, but is very convenient nonetheless. Overlapping the visible and ir beams is easily accomplished on a large (2m x 3m), flat, preferably magnetic, table (or several tables) as follows (refer to figure 3):

a) With the BA-1 box temporarily removed, set up an HeNe laser and mixer beam splitter S2 so that a red beam is generated approximately 11.1 cm above and parallel to the table top. A height gauge is essential for accurate work. The mixer S2 is specially coated so that it reflects 95% of the red beam and transmits about 85% of the 1.06 μm beam.

b) Place the retro-mirror M3 in the red beam at the extremity of the available working space and direct the beam back on itself so that it returns exactly to the HeNe laser. This is a trivial operation if M3 is in a gimbal mount.

c) The red beam from M3 will also emerge from the mixer S2 in the direction of the steering mirror M2. The mixer beam splitter S2 is wedged at about 1/2 degree, and the beam, of course, tends to refract toward the base of the mixer, so that the wedge of the latter must be properly oriented in its gimbal mount to keep the beam at a constant distance from the table top (base of wedge to the right in figures 3 and 4).

d) The red beam will now be collinear with the ir beam if the two coincide at mirrors M2 and M3. This is easily accomplished by putting a piece of lens tissue over each mirror in turn, using an ir viewer to observe the spots, and adjusting the upstream mirror in each case to make the spots overlap.

e) Now that the red and ir beams are collinear the ir beam is blocked off, and further alignment is done with the red beam. This consists of making sure that the emerging beams are centered in their ports and are in the proper plane above the table top. Most of this adjustment has been done on the BA-1 box before delivery.

f) The retro-mirror M3 is now removed and replaced with a power meter.

Note #1: Due to dispersion in the prisms, the red and ir beams will not exactly overlap on all beams. The maximum difference in overlap of beam centers is about 1.3 mm at 1 m distance from BA-1.

Note #2: Once the BA-1 box is inserted in the collinear beam, the retro-mirror M3 will no longer be in the proper location to reflect the red beam back on itself. If further checks are desired to insure overlap of the red and ir beams, M3 will have to be moved slightly and readjusted as before.

## 5. CLEANING OF BEAM SPLITTER SURFACES

As indicated earlier, experimental work at NBS indicates that scatter from the beam splitter surfaces due to surface roughness, dust, and general contamination can have a significant effect on the intensity in the m = 4 beam. Significant scatter occurs even shortly after the beam splitter has been cleaned. Surface contamination due to smoke, aerosols, and oil mist from vacuum pumps can aggravate this problem. For this reason, measurements on the m = 4 are not recommended. However, for the supersmooth beam splitter presently in use in BA-1, the m = 3 and lower order beams seem to be stable with time in a normal laboratory environment, at least for many months.

Should cleaning of the beam splitter be necessary, we recommend the technique described by Heinisch [6] as follows:

a) Soak the element for several hours in hot detergent solution (made from filtered, distilled, deionized water).

b) Rinse with filtered, distilled, deionized water (hereafter referred to as water) and then gently rub with a saturated cotton ball until the entire surface has been covered.

c) Rinse the surface with water and examine for a water break where the water does not maintain a uniform continuous film. If some portions do not pass the water break test, repeat b) and c) until they do.

d) The surface covered with water is blown dry with a jet of dry, oil free nitrogen. This is begun at the highest point and continued with horizontal sweeps to the bottom of the surface. Care should be taken not to permit water droplets from the edge to flow across the dry area.

e) Inspect by illuminating the surface with a collimated beam of visible light with approximately the spectral distribution and illuminance of sunlight. The surface should be viewed in a darkened room against a black background.

f) If step e) shows the surface to be clean, proceed to measure scatter levels; if not, repeat steps b) - e).

The glass neutral density filters should not require cleaning, but if soiled with a fingerprint or something similar, the same procedure outlined above can be used.

## 6. ATTENUATION ACCURACY

The attenuation ratios of the various beams emerging from the BA-1 box have been calculated theoretically for an unpolarized laser and listed in table I. The attenuation ratios for the preattenuator S1 have also been calculated for an angle of incidence of -5° and listed in table III. The optical densities tabulated in table II were measured experimentally with pyroelectric detectors equipped with a digital readout. The uncertainties associated with these values will be analyzed.

### 6.1 BA-1 Error Analysis

The attenuation properties of BA-1 are determined solely by a 2 degree wedged fused silica beam splitter. This is a stable, well-characterized device which allows us to calculate most of the expected errors contributing to the attenuation uncertainties of the various m orders. An additional systematic error is due to the incoherently scattered radiation at the surface of the beam splitter, which will be considered separately.

The $m^{th}$ order attenuation ratio $R_m$ is a function of the index of refraction n, wedge angle w, angle of incidence A, polarization P, and temperature T;

$$R_m = f(n,A,B,P,T). \tag{1}$$

This function cannot be put in closed form, but is easily programmed on a computer (see [2]). The systematic error $\delta R_m$ in $R_m$ caused by a systematic error in variable $x_i$, $\delta x_i$, is given by

$$\delta R_m = \frac{\partial f}{\partial x_i} \delta x_i \tag{2}$$

where the quantity $\frac{\partial f}{\partial x_i}$ represents the usual rate of change in f with respect to the variable $x_i$ at the operating point of f, and the other $j \neq i$ variables being held constant. These slopes can be estimated numerically by varying the appropriate parameters in the same computer program that was used to determine $R_m$. The $dx_i$ denotes the estimated uncertainty in the value of variable $x_i$. This procedure is used with all the $x_i$ variables. A conservative method of determining total uncertainty is to sum the individual errors of the constituent variables, or

$$\frac{dR_m}{R_m} = \frac{1}{R_m} \sum_{i=1}^{j} \left| \frac{\partial f}{\partial x_i} dx_i \right| \tag{3}$$

where the j variables are given in eq. (1), and we have expressed the total estimated uncertainty as a fraction. The estimated uncertainties $dx_i$ were computed as follows:

Wedge angle w. The wedge angle inaccuracy dw was taken to be .06°. This figure represents the 95% confidence limits on wedge angle measurements.

Angle of incidence A. The error in the angle of incidence can be kept less than dA = .38°. A variation of this magnitude would be evident as a 2 mm shift in the position of the laser beam in one of the BA-1 exit ports, which is easily observable and can be corrected by realignment.

Index of refraction n. The index of refraction used in our computer program was taken from the data of [7] at 293 K. This work documents observed sample-to-sample variations in n. In particular, the maximum variation of n for samples of fused silica obtained from different sources was about ± .000028, and we assumed dn in our error analysis to be of this value.

Polarization P. The data in table I are for unpolarized (or pure circularly polarized) radiation. Table I should also be used if the polarization state is unknown. The maximum polarization error occurs for either completely vertical or completely horizontal polarization. These effects can be calculated from the computer program. If the polarization is plane polarized in either a vertical or horizontal direction, then the attenuation ratios in table IV can be used to yield an improved accuracy. However, we take the view that, for BA-1 to be a useful device, we should not require any information on input laser polarization. In this case table I should be used. Polarization uncertainties will often dominate the overall uncertainty in attenuation ratios.

Temperature T. The beam splitter attenuation ratios are dependent on temperature since n is a function of T. This dependence is given approximately by the relation [7]

$$\frac{\partial n}{\partial T} = 10^{-5} \qquad (4)$$

or $|dn| \simeq 10^{-4}$ for $|dT| \simeq 10$ k around 293 K.

Scatter. This contribution to the total uncertainty in $R_m$ must be considered separately from the other variables since it cannot be accurately calculated. Experiments to measure the magnitude of the scatter are described in reference [2]. The maximum observed variation of $R_m$ due to this effect was 15% on the m = 4 beam. The importance of scatter diminishes as the order number m decreases.

The above BA-1 uncertainties have been listed in table V. As stated before, we do not recommend use of this m = 4 beam due to the large scattering errors. For other orders it can be seen that the total estimated uncertainties are less than 3.5%.

Table IV. BA-1 attenuation ratios for polarized laser input.

| Vertical Polarization Beam Ratio Relative to m=0 Beam | 1.06 μm | .6328 μm | .5145 μm | Total Max. Estimated Uncertainty[(a)] % |
|---|---|---|---|---|
| (m=0)/(m=-1) | 26.79 | 26.05 | 25.60 | .11 |
| (m=0)/(m=+1) | 29.25 | 28.49 | 28.03 | .04 |
| (m=0)/(m=2) | 864.9 | 820.4 | 794.6 | .08 |
| (m=0)/(m=3) | 25,680 | 23,710 | 22,600 | .69 |
| (m=0)/(1N) | .9322 | .9304 | .9293 | |

| Horizontal Polarization Beam Ratio Relative to m=0 Beam | 1.06 μm | .6328 μm | .5145 μm | Total Max. Estimated Uncertainty[(a)] % |
|---|---|---|---|---|
| (m=0)/(m=-1) | 28.68 | 27.88 | 27.40 | .11 |
| (m=0)/(m=+1) | 30.12 | 29.33 | 28.86 | .04 |
| (m=0)/(m=2) | 897.5 | 850.8 | 823.8 | .08 |
| (m=0)/(m=3) | 26,640 | 24,590 | 23,430 | .69 |
| (m=0)/(1N) | .9353 | .9335 | .9325 | |

Table V. Error budget for BA-1.

Percent change in beam splitter ratio.
(Absolute value at .6328 μm)

| Error Source | Order Number | | | | |
|---|---|---|---|---|---|
| | -1 | +1 | 2 | 3 | 4 |
| 1. Index variation max. sample variation | < .01 | < .01 | .02 | .03 | .04 |
| 2. Wedge angle uncertainty | < .01 | < .01 | < .01 | < .01 | < .01 |
| 3. Angle of incidence variation | .02 | < .01 | .01 | .01 | .01 |
| 4. Polarization max. variation | 3.39 | 1.46 | 1.82 | 1.81 | 2.13 |
| 5. Temperature-variation ± 10 K from 293 K | .04 | .04 | .07 | .10 | .14 |
| 6. Scatter | < .01 | < .01 | .02 | .52 | 15 |
| 7. Total uncertainty | 3.5 | 1.5 | 1.9 | 2.5 | 17.3 |

It should be emphasized that the attenuation ratios as well as the expected errors are largely calculated values based on the computer program described in [6]. Many experiments have been performed at NBS to test the validity of this program. Some of these experiments are described in [6] and [7] where theory and experiment are compared. We have no experimental evidence to indicate that our theoretical predictions are incorrect. Because we believe the experimental determination of attenuation ratios is inherently less accurate than calculation, only the theoretical values of $R_m$ are tabulated here. The only experimental measurements made on BA-1 were to check that BA-1 was a member of the set which possesses the characteristics assumed in the computer program. That is, we measured the wedge angle and $R_m$ at one wavelength to assure that the beam splitter material was fused silica. The measured $R_m$ was within the 95% confidence limits of the predicted computer value.

The uncertainties in table V are calculated at .6328 μm. The changes in these values for other wavelengths are negligible.

## 6.2 Neutral Density Filter Error Analysis

The systematic errors which can be calculated for the absorbing glass neutral density filters are described at length in [7] and will not be elaborated on here. They are summarized in table VI along with their estimated maximum values. In addition we have tabulated the measured filter uniformity. This was checked with a 1 mm diameter HeNe laser beam, and the maximum edge-to-edge density excursions are listed. The measured attenuation imprecision varies from filter to filter and is generally greater for the higher densities. The values listed in table VI represent 95% confidence limits of measurements made on the respective filters. The systematic measurement inaccuracy is associated with the non-linearity of the pyroelectric detectors and is estimated by the designer of these instruments at about 4%. As before, the total uncertainty is conservatively figured as the linear sum of the various systematic and random errors and is given in the bottom line of table VI. Obviously, these errors can be reduced if care is exercised in the use of these filters in any practical experimental configuration. The bottom line uncertainty represents the maximum or worst case estimate of error. These stated values were not determined for all wavelengths, but the wavelength dependence is expected to be negligible.

It can be seen that the uncertainties are, in general, much greater than those of BA-1, and consequently these filters should not be used in applications requiring the greatest possible accuracy.

Table VI. Error budget for neutral density filters.

Percent change in attenuation at .6328 μm.

| Known Error Source | Density .2 | .5 | 1.0 | 2.0 | 3.0 |
|---|---|---|---|---|---|
| 1. Impedance in filter (maximum) | 5.3 | 2.6 | .8 | < .1 | < .1 |
| 2. Tilt at 3° angle of incidence | < .1 | .1 | .1 | .3 | .4 |
| 3. Temperature variation ± 10°C from 20°C | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 4. Uniformities. Max. measured variation from average @ .6328 μm | 1.0 | 1.3 | 3.6 | 4.8 | 7.0 |
| 5. Measurement imprecision (at .5145 μm measurements) | 1.3 | 0 | 9.6 | 8.6 | 6.1 |
| 6. Systematic measurement inaccuracy (Deviations from linearity) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Total estimated max. uncertainty (%) | 14.6 | 11.0 | 21.0 | 20.7 | 20.5 |

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Measurement procedures are described for the step attenuation of laser beams up to 44 dB using a specially constructed attenuator box ( BA-1 ). With the use of an additional preattenuator beam splitter, the attenuation range can be extended to over 70 dB. The BA-1 system is designed for use at .6328µm, .5145 µm, and 1.06 µm. The attenuation ratios of these wavelengths are calculated values. An analysis of the estimated uncertainties is also given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Attenuation; laser attenuation; optical beam splitter

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