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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Laser Attenuators for the Production of Low Power Beams in the Visible and 1.06 μm Regions

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LASER ATTENUATORS FOR THE PRODUCTION OF LOW POWER BEAMS IN THE VISIBLE AND 1.06 μm REGIONS

by

B.L. Danielson and Yardley Beers

Abstract

Some methods were investigated for the accurate attenuation of laser beams to very low levels; approximately 10^{-11} watts. This work was done at 1.06 and .6471 μm, but the conclusions are applicable throughout the visible region as well. Two types of devices were considered; wedged beam splitters and neutral density filters. The theory of the attenuation of a wedged beam splitter was described and some of the errors associated with these devices were discussed.

Key words: Beam splitter; laser attenuation; neutral density filter.

1. Introduction

Many different proposals have been made for the accurate attenuation of laser radiation. Some of these methods have been described in detail in review articles by Heard [1] and Birnbaum [2]. They include scattering from a diffuse Lambertian surface, integrating spheres, wire grids, polarizer-analyzer combinations, gratings, silicon wafer devices, beam splitters and absorbing filters. Double prism attenuators based on the principle of total internal reflection have also been reported [3]. We report here an investigation of techniques for the production of a very low intensity beam of approximately 10^{-11} watts (repetitively Q-switched or cw). Our main interest was at a wavelength of 1.06 μm. We feel that beam splitters and absorbing neutral density filters offer the best means of obtaining such a low level beam in a configuration useful in comparing the response of detectors relative to standard power meters or calorimeters. If properly employed these attenuators maintain the Gaussian character of propagating laser beams which is desirable for our application. Also, they do not depend appreciably on the polarization of the laser radiation. The only other type of attenuator which was considered was the liquid cell absorber suggested by Birnbaum [2]. A cell filled with, for example, a solution of $CuSO_4$ in water, can be made with any arbitrary attenuation by simply adjusting the cell length or concentration. This device was rejected, however, because the heating effect of the absorbed laser radiation causes convection currents, and the resulting turbulence produces an undesirable distortion of the propagating beam.

Most of our attention during the course of the present study was directed toward what we felt was the most promising device for accurate laser attenuation in the visible and at 1.06 μm. This was the wedged, fused silica beam splitter. A general theory was developed from Fresnel's equations which predicts the attenuation of any order beam for an arbitrary angle of incidence, index of refraction, wedge angle, and polarization. Experimental results at both visible and IR wavelengths were in general agreement with the theory.

Neutral density filters were also considered as attenuators. Some observations are presented regarding errors associated with the use of these devices.

Finally, a practical procedure was demonstrated for obtaining a beam of about 10^{-11} watts in an experimental arrangement useful in determining the linearity and calibration of an IR detector. This involved attenuating the output of a YAG laser by about 110 dB. An overall accuracy estimate was made on the attenuated output beam.

2. Attenuation Methods

The general plan of this calibration method assumes the existence of a laser beam which is much more powerful than needed for the experiment. This is attenuated down to a convenient level which can be calibrated directly by a calorimeter or other device, and then it is further attenuated to a level suitable for observation by the low level detector. The first of these two attenuations need not be calibrated, but for convenience, it should be constant. The second needs to be calibrated as accurately as possible and to be capable of holding its calibration.

There are several physical phenomena which can be used to attenuate laser beams: interference, reflection, absorption, and scattering. We will examine two types of attenuators which are based on reflection and absorption respectively.

2.1 Wedge Beam Splitters

The usual way of attenuating a beam by reflection is by the use of a wedge beam splitter, which consists of a prism of glass with a very small apex angle, usually about one degree. If a narrow pencil beam of light is incident at one point on one surface, it is refracted into the prism and then is internally reflected successively by the two surfaces (see figure 1). At each encounter of the internal beam with a surface, a beam emerges by refraction, and each emergent beam is weaker than the previous one.

The principal advantage of such a device is that ideally it dissipates little or no power and therefore it undergoes very little heating, and the attenuation factor between the incident beam and any selected emerging beam is essentially independent of power level. Also it can be expected to vary only slowly with wavelength. In addition, to a fairly good approximation, the properties of the device can be predicted from theory. A major disadvantage is that the attenuation factor can not be varied easily or arbitrarily selected. The attenuation factor depends almost entirely upon the index of refraction of the glass, varying between about ten to twenty-five per reflection for the types of glass generally employed in the visible region. A second disadvantage is the polarization dependence of the reflection, but by use of a very small wedge angle and by a proper choice of the angle of incidence, this effect can be kept small, and, under practical conditions, this disadvantage is not serious. The device, of course, is affected by dirt on the surface and imperfections in the glass, and therefore the theory does not hold exactly. Physically, these effects give rise to scattered light, but its presence can be detected by observing with the detector at different distances from the splitter. The portion of the beam due to the laser should not vary in total power with distance, assuming that the detector aperture is sufficiently large, while the scattered power is expected to vary inversely with the square of the distance. Therefore, if one extrapolates the measured power to infinite distance quadratically, he obtains the power of the laser beam alone. This effect is important only with beams that have been reflected several times.

The theory of this device has been discussed in detail in a separate communication [4] to which we shall refer to as I. A few of the principal concepts and results are summarized here.

In figure 1, each emerging beam is labeled by an index m, which denotes the number of reflections the light has undergone between incidence and emergence. This quantity will be referred to as the "order" of the beam. In general, there is only one beam of each order, those of even order emerging in the forward direction and those of odd order in the backward direction. To a good approximation, if the wedge angle A is small, the angle between successive beams on the same side is 2NA, where N is the index of refraction.

However, as a special case, there are two beams of the first order, one denoted by -1 having been reflected from first surface, and the other, denoted by +1 having been reflected from the second surface. The + and - signs are arbitrary labels for distinguishing between these two beams and have no further significance.

The fraction of the power contained in the beam which is transmitted and that which is reflected can be calculated by well known formulas. These are summarized in I. In general, these fractions depend upon the state of polarization, but polarization effects disappear for normal incidence and are small for small angles of incidence.

There is an implied sign convention for the angles depicted in figure 1. All of the angles are positive as shown. If, in some other situation, any incident beam should appear on the opposite side of the normal than that shown, the associated angle of incidence should be considered negative. Once A, N, and the angle of incidence B are given, values of all the other angles can be calculated by well known methods of geometry and geometrical optics. Reference [1] gives explicit formulas for these angles, and these may be inserted into the formulas for the reflectivity and the transmissivity for the individual encounters of the beam with the interfaces to calculate the total attenuation for any beam relative to the incident beam.

Using these theoretical procedures, a computer program has been developed for computing the angles and attenuation factors. This program contains a provision for plotting the results graphically. One sample is repeated here from I in figure 2. This sample pertains to the third order ($m = 3$) and for a wedge angle A of 1°. The graph in the upper left pertains to an index of refraction of 1.75. For the incident light polarized perpendicular to the plane of incidence, it gives the attenuation factor as a function of the angle of incidence B. The attenuation factor has been normalized to its maximum value, which is listed in the upper left corner.

The graph in the lower left corner gives the ratio of the attenuation factor for the parallel polarization to that of the perpendicular polarization as a function of the angle of incidence for the same parameters as for the graph above. It is to be noted that it reaches a minimum of about 1.005 at $B = -3.0°$, so that, if the state of polarization is unknown or changes from that assumed, the maximum error that can result is less than one percent if this angle of incidence is used.

The other two graphs are analogous to the ones on the left except that the index of refraction has been changed from 1.75 to 1.50. The main effect of this change is to increase the attenuation factor.

By examination of a number of graphs of these types it has been possible to draw some conclusions: (1) The minimum polarization effects seem to occur at the same angle as the maximum attenuation for the perpendicular polarization. Obviously for optimum performance this angle should be used. (2) Except the -1 beam for which it is zero, this optimum angle is negative, and its value increases in magnitude with the order number m and with the wedge angle A. (3) The polarization effects increase with increasing wedge angle A.

How this optimum angle of incidence varies with the order m, the wedge angle A, and the index of refraction N is indicated by table I.

The theory was compared to experimental data obtained on a fused silica beam splitter. For convenience the preliminary comparison was made in the visible region. A one half watt krypton laser was used as a source of radiation at .6471 μm. Great care was taken to clean up the profile of the beam by focusing it down to a small size in the plane of a small aperture, which filtered out some spurious beams. This spatial filter was located about one meter from the laser. The beam then diverged until it passed through a lens of 4 M focal length located about 5 M further down the beam. The spacings between this lens and the beam splitter and from this splitter to the detectors varied during the measurements but were from 1 M to 3 M. The principal portion of the beam was about 6 mm in diameter and it was about 3 mm in diameter at the apertures of the detectors. This central portion was surrounded by a weak halo of much larger diameter, which was noticeably augmented by passage through the splitter as the result of scattering. However, a light trap just larger than the central portion was put in the beam and the remaining light was brought to a focus on a calibrated detector. It was found in this way that the power conveyed in the halo amounted to only a few parts in 10^4 of the entire beam. The fact that this weak halo was visible is an indication of the great sensitivity of the human eye. The theory of the propagation of laser beams through lens systems has been discussed by several authors [5,6]. This theory was used in the design of the present optical system.

The index of refraction N and the wedge angle A were determined experimentally by the methods suggested in I. The ratio between the zero order and -1 order beams at normal incidence was measured by the use of two NBS calorimeters and was found to be 26.496 ± 0.073, corresponding to an index of refraction of 1.46138 ± 0.00073. (Stated errors in this paragraph and in table I are 95% confidence limits.)

These data were used to compute the ratio of the intensities of the zeroeth order beam to those of the +1, 2, 3 and 4th order beams (for the perpendicular polarization). These results are listed in the first column of table II. Experimental values are listed in the second column. The agreement is satisfactory.

The ratio between the zeroeth and +1 orders was measured directly by the use of two NBS calorimeters. It was not practical to measure the other ratios directly. With these the accuracy was limited by the signal-to-noise ratio of the low level beam, and to keep this a minimum it was necessary to use the maximum available power from the laser and the longest feasible observation times, 300 sec. Under these conditions a calorimeter used on the zeroeth order beam would be overloaded. Therefore the ratios of these higher order beams were measured relative to the -1 beam, and since the ratio between the zeroeth and -1 beams had been determined previously, these higher order ratios could be computed. The 2, 3, and 4th order beams were observed using an NBS pyroelectric detector, whose analog output had been modified to use a 6 sec time constant. The pyroelectric detector output was recorded on a second data acquisition channel, the first being used for the calorimeter on the -1 beam. The data were processed by a special computer program. It was assumed that the pyroelectric detector was linear throughout the range.

In the case of the M = 3 and M = 4 beams, measurements were made at two different distances and the results were extrapolated quadratically to infinity to correct for radiation scattering at the surfaces of the beam splitter. At one meter, about 2% of the M = 3 beam was due to scattering, while for the M = 4 beam at this distance about 14% was due to scattering.

In table II the uncertainties assigned to the calculated values are due to imprecision in the quantities (index of refraction, wedge angle) which are used in the theoretical prediction of attenuation ratios. The corresponding uncertainties assigned to the measured values represent a spread in the experimental data due to noise in the detector and electronics as well as any possible systematic shifts (excluding radiation scattering). As noted above, the estimated scattering effects have been corrected for. It is difficult to unfold the systematic errors from the noise in data such as this. Nevertheless, we can assert that the theoretically predicted attenuation ratios for m = 1, 2, 3 agree with our experimental values to within a few percent.

The corresponding data obtained on beam splitter ratios at 1.06 microns is presented in table III. A 2 watt current regulated NdiYAG cw laser was used for these measurements. They were obtained in much the same way as described previously for the measurements at .6471 μm with the exception that the wedge angle (1.02 deg.) was assumed to be known, and no corrections were made for scattering. All the runs were made with detectors about 2 meters away from the beam splitter. The most accurate measurements are those taken with calorimeters and, due to intensity limitations, this can be done only with the m = 0 and m = -1 orders. Pyroelectric detectors were used with the remaining beams. It will be noticed that there is somewhat less noise in this data relative to that in table II. This is due to an improved measurement system that eliminated some of the noise responsible for fluctuations in the experimental values. With the improved data acquisition system a total of sixteen runs were made of the m = 0 to m = -1 ratio using C-series calorimeters. Runs were made on both surfaces and before and after cleaning with a vapor degreaser. The total standard deviation was .032 or about .1%. Before cleaning, the beam splitter had remained for a year in a laboratory environment containing vacuum pumps and soldering facilities and no special precautions were observed to insure cleanliness of the beam splitter surfaces. One may infer, then, that the m = 0 to m = -1 ratio at least is not overly sensitive to surface contamination.

As before, the index of refraction was calculated from this m = 0 to m = -1 beam splitter ratio. The value thus obtained (1.4526) differs slightly from the handbook value (1.449746). Presumably the measurement of n determined in this way compensates for some scattering errors. At any rate theoretical beam splitter ratios using the measured N tend to be in better agreement with experimentally determined attenuation ratios of the higher orders.

2.2 Neutral Density Filters

Neutral density filters are optical attenuators designed to have fairly constant opacity over a wide wavelength region. The degree of attenuation is customarily specified by "optical density" which is the logarithm to the base 10 of the intensity of a beam incident upon one surface divided by the intensity of the beam which emerges from the other surface. This definition includes both reflection and absorption losses. Thus a filter of density 2.0 attenuates an incident beam by a factor of 100. Many different types of neutral density filters are commercially available [7]. Most of these are not suitable for the present application due to excessive amounts of scattering or reflection. The only types considered for the present investigation were absorbing glass filters available from numerous distributors. These have the property that they may be stacked, or used in cascade, to achieve any desired density (in increments of optical density of .1).

Unlike fused quartz beam splitters, the behavior of these filters, being commercial proprietary products of unknown composition, cannot be predicted reliably. Data obtained on one filter cannot be assumed to apply to one made by another manufacturer or even to one made by the same manufacturer at another time. All these conditions are, of course, undesirable from a standards point of view. Nevertheless from information available in the open literature [13,14] and our own experience, we feel that the glass neutral density filters can be sufficiently well characterized to be useful for measurements of low level laser beams if proper precautions are observed. In the following sections we shall examine some filter properties and effects which could cause errors and uncertainties in systems employing these devices.

1) Interference in the Filter

Under appropriate conditions of illumination it is possible for the reflection from the front and back surfaces to interfere, producing variations in apparent attenuation. The ratio of maximum transmission (constructive interference) to minimum transmission (destructive interference) is given by:

$$\frac{I\ max}{I\ min} = \frac{(1-Re^{-\alpha})^2 + 4Re^{-\alpha}}{(1-Re^{-\alpha})^2} \qquad (1)$$

where R is the intensity reflection coefficient for a single surface and α is the intensity absorption coefficient for the volume absorbing filters. Some values of this function are given in table IV. Interference of this sort requires precise alignment and perfectly parallel beams. The more commonly encountered situation where these conditions do not exactly hold gives rise to rings or successive regions of constructive and destructive interference. In this case the corresponding intensity ratios would be somewhat less than those given in the table.

2) Interference Between Filters

It is also possible for reflections between successive filters to produce interference effects of the type mentioned above. Since in this case the beams combine in an air space, the magnitude of the effect may be determined from table III or eq. (1) by putting α equal to zero. This type of interference effect is easily avoided, however, by simply tilting the filters a degree or so relative to any adjacent filter. The small translation of the beam thus produced is negligible.

3) Tilt

Apparent changes in attenuation also occur when the incident beam is no longer normal to the filter surface. This is due to two effects:

a. The reflectivity changes with angle of incidence, and

b. the path length of the beam through the absorbing medium changes.

The resulting fractional changes in transmission are given in tables V and VI for a filter with an index of refraction equal to 1.5. As can be seen, these effects are negligible for small angles of incidence.

4) Temperature and Power Variations

With high density filters most of the power in the incident laser beam is absorbed near the first surface of the first filter in a stack. If the power level is sufficiently high the filter is heated with a consequent change in attenuation factor or even with permanent damage. Measurements were made on a density 2.0 filter at power levels of 13.5 and 116 mW (beam size approximately 4 mm^2) for 300 sec and the apparent density decreased by about two percent at the higher power level. That the filter was power and temperature sensitive was further demonstrated qualitatively by

a. bringing up a heat gun and causing the beam to be distorted, and

b. changing the size of a 125 mW beam by use of a lens and showing that there was a change in the apparent density.

This same 2.0 filter was put in a temperature controlled box, and it was found that the fraction of the beam transmitted (not the density) increased about .3% per C°. A similar result was obtained with a density 3.0 filter, but a 1.0 filter appeared to have no change in transmission.

5) Saturation

The laser beam may not only heat up the filters but at some level may actually cause bleaching. This has been observed in some colored glass filters [9]. The manufacturer of the filters under investigation specified that no bleaching occurs with a one millisecond pulse of 300 joules/cm^2. However, we did not attempt any bleaching studies.

6) Uniformities

Three filters were tested for geometrical uniformity by scanning across the filters along both center lines in steps of one beam width (4 mm). The density .9 and 1.0 ones were found to have no variation within the precision of the experiment (1%). However, a 2.0 one was found to vary by 20% in scanning from one edge to the opposite edge.

7) Stability

No data have been taken on the variations with time. Control charts, such as described by West [8], should be maintained on any filter used in an actual calibration system.

8) Combination Effects

The densities of a .6 and a .9 filter were measured and compared with the apparent density of the two in a stack, and the agreement was excellent. This experiment was repeated with a .9 and a 1.0 filter with the same result.

9) Scattering

Considerable forward diffuse scattering can occur in neutral density filters. Some types of filters are much worse than others in this regard [7]. It is important that measurements on absorption are made using the same sort of geometrical layout as is used in the final calibration system.

3. Experimental Measurements

The arrangement illustrated in figure 3 represents one possible configuration for obtaining a 10^{-11} watt beam. Many other equally valid approaches are possible. With the present system, we used a YAG laser, which can be Q-switched, with a nominal 1 watt average power output. To facilitate alignment of the low intensity beams emerging from beam splitter #2, a visible beam from a Kr ion laser was adjusted to be collinear with the YAG laser beam in beam splitter #1. If the two lasers are arranged so that the visible zero order beam overlaps the IR second order beam, then the alignment laser is very little attenuated while the IR laser intensity is reduced 29 dB to about 1 mW, which is a convenient level for measurement purposes. This requires about a 6° difference in angle of incidence for the two beams impinging on a beam splitter with a 2° wedge.

We utilized the third order reflection in beam splitter #2 since, as discussed previously, this is probably the maximum attenuation which can be used without excessive scattering losses. The third order output of a fused silica beam splitter has an equivalent optical density of 4.4 (an attenuation ratio of 2.5×10^4 or 44 dB). The YAG laser beam emerging from the beam splitter at this intensity is not observable with most conventional IR viewers, but the collinear visible beam can be used for alignment of subsequent optics. Actually the visible (.6741 μm) and IR (1.06 μm) beams are no longer exactly collinear due to dispersion, but the deviation is only about .03 degree and this can be safely neglected. At this point further attenuation of 36 dB was most conveniently effected with previously calibrated neutral density filters. The total system attenuation is then about 109 dB. The filters of density 2, .8, and .8 were alternately tilted by about 2 degrees from the incident beam. It should be noted, however, that the nominal densities of a filter may depart drastically from the actual measured values. Each filter must be thoroughly calibrated and checked for various types of non-uniformity under the conditions it will be used.

This arrangement also allows for monitors on beams of other orders. Linearity of the detector and amplifier system can be checked at these points.

Up to this point we have considered only attenuation of a cw laser. However the system illustrated in figure 3 can also be used to attenuate output beams from repetitively pulsed lasers with the same attenuation factor applying to the average energy per pulse and the peak power per pulse. Power dependent effects should be negligible in this type of experimental configuration. If the YAG laser in figure 3 is repetitively pulsed at frequency f, we may easily determine the average energy per pulse $\overline{E}$ in the final outbeam from a measurement of the average power $\overline{P}_o$ in the m = 0 beam. The time constant of this power meter should be much greater than f^{-1} which will be true for most thermal detectors. Then $\overline{E}$ is given by

$$\overline{E} = \frac{\overline{P}_o}{Bf}, \qquad (2)$$

where B is the attenuation factor of the beam splitter-neutral density filter combination. In the present case $B = 1.096 \times 10^8$ for an angle of incidence on BS#2 of 1.0 deg. and unpolarized radiation. This arrangement results in about 10^{-15} joules per pulse at a repetition rate of 10 kHz.

4. Conclusion

On the basis of the foregoing experiments we believe that the fused quartz wedged beam splitter offers much promise as a precision laser attenuator in the wavelength range where quartz is transparent (.3 to 2 μm). Fused quartz is a material which is stable, well characterized and can be polished without didifficulty to an rms roughness less than 15 nm. The optical absorption [12] at 1.06 μm is very small (less than 10^{-4} cm^{-1}), and the index of refraction does not vary more than a few parts in 10^4 from one manufacturer to the next [11]. In the configuration we employed the difference in values of attenuation calculated from Fresnel's law and mean experimental values was less than 5% up to third order reflections. Scattering corrections were significant for the fourth order reflection (as large as 15%), but these may be minimized by employing a superpolish surface finish and careful cleaning procedures.

Absorption type neutral density filters are not as well characterized as wedged beam splitters, but if their properties are carefully measured they can also be useful as low-power laser attenuators. Attenuation uncertainties due to interference effects, non-uniformity, tilt, and temperature changes can probably be kept less than 10%. The effect of aging on attenuation is unknown. More exact estimates of uncertainties must be determined by continuing measurements of the attenuation ratios of individual filters under actual conditions of use.

5. Acknowledgments

D.J. Jennings and T.W. Russell actively participated in the direction of this project during its early phases, and their contributions are gratefully acknowledged. The authors also wish to thank W.E. Case and Carla Selby for their able assistance.

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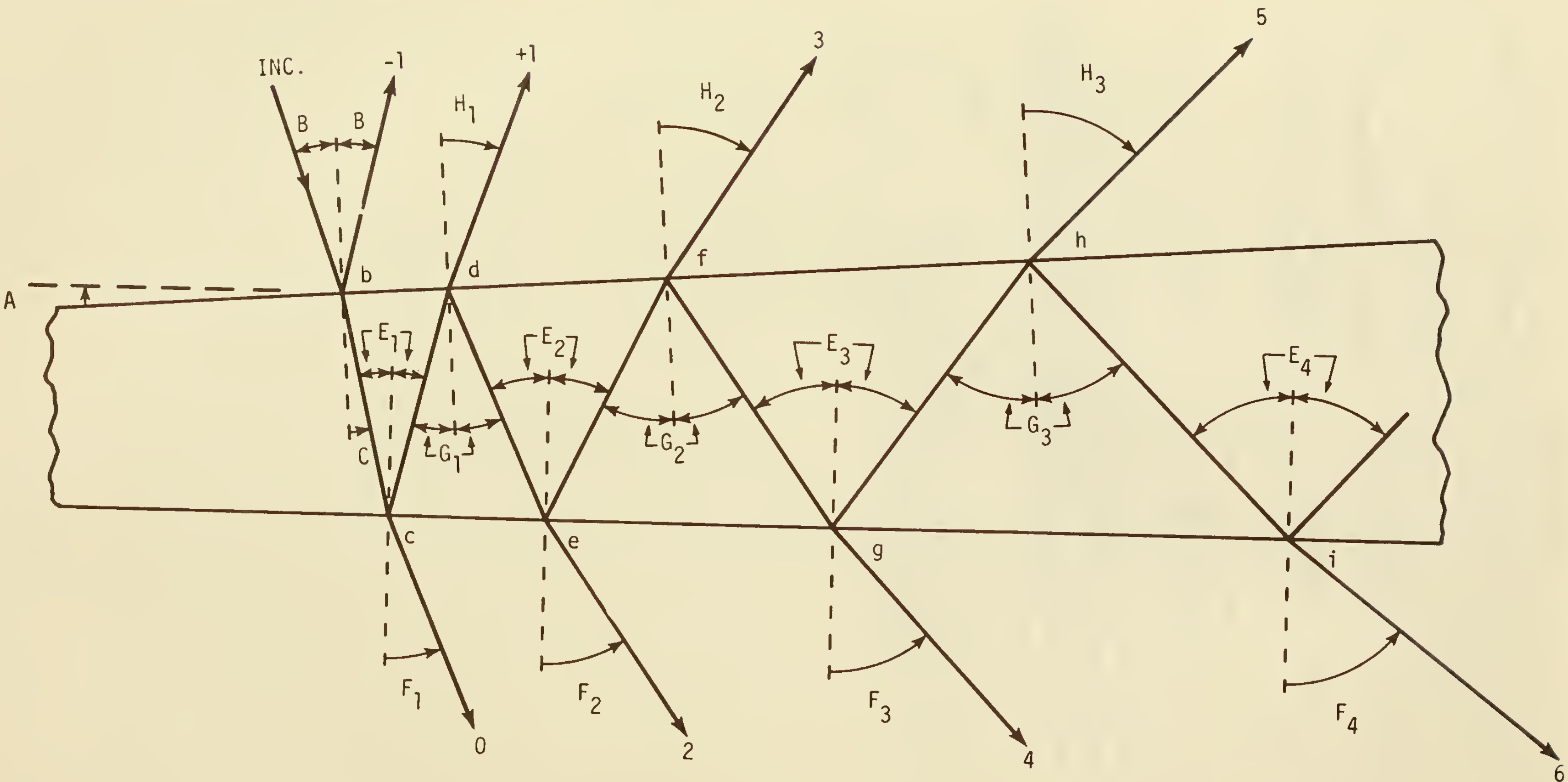

Figure 1. Propagation of a pencil beam in a wedge of small angle A.

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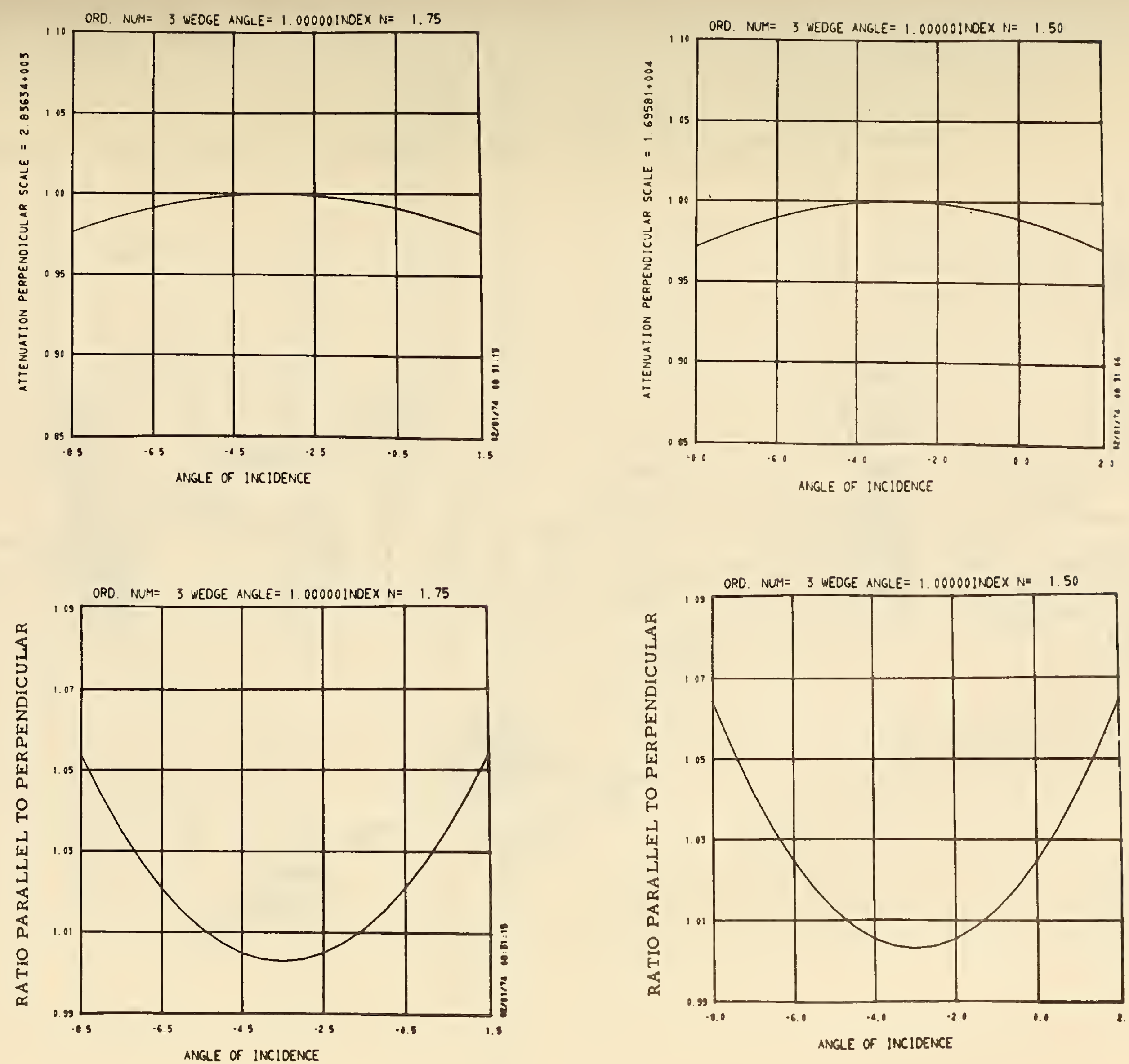

Figure 2. Ratio of parallel to perpendicular attenuation and relative attenuation as a function of angle of incidence.

76 x 1619

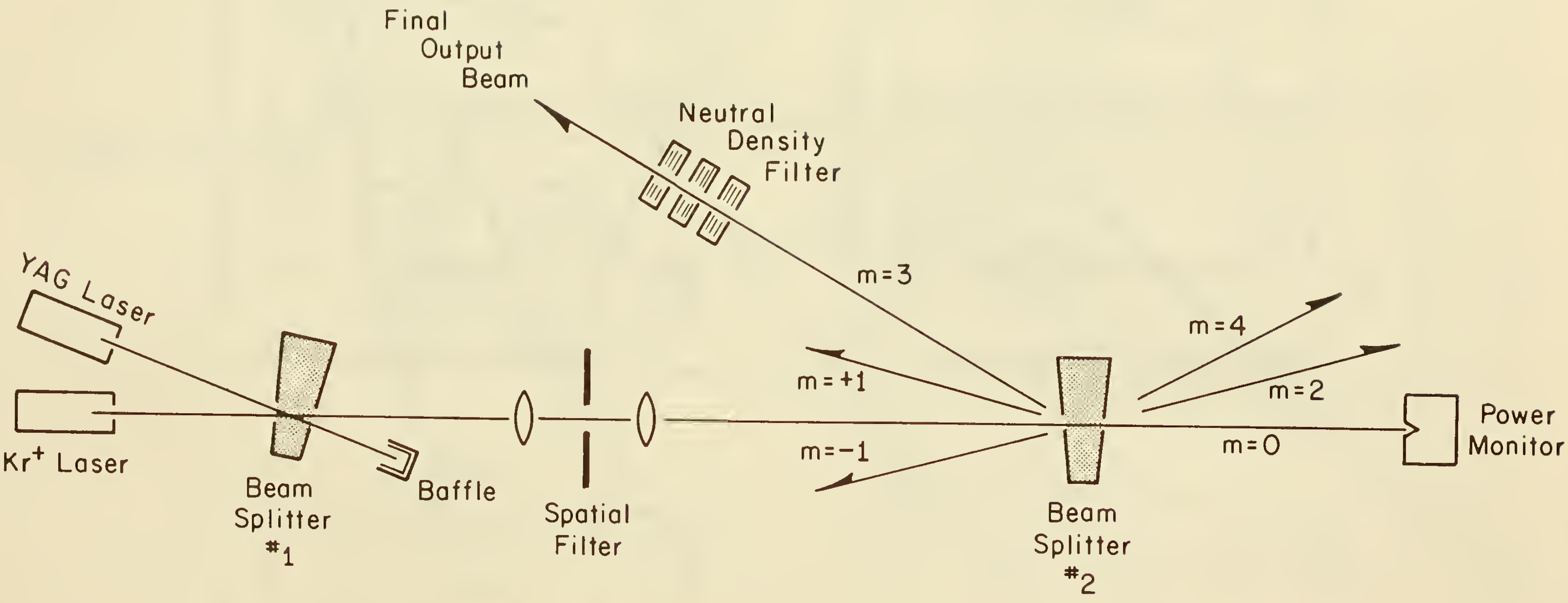

Figure 3. Experimental configuration for obtaining a low level beam.

76 x 0753

Table I

Optimum angle of incidence B

	Wedge Angle 1°		Wedge Angle 2°	
Order	N=1.5	N=1.75	N=1.5	N=1.75
-1	0.0	0.0	0.0	0.0
+1	-1.5	-2.0	-3.0	-3.5
2	-2.3	-2.7	-4.5	-5.5
3	-3.0	-3.5	-6.0	-7.0
4	-4.0	-4.5	-7.5	-9.0

Table II

Fused silica beam splitter ratio of intensity of zeroeth order beam to beam of order m at .6471 μm. Angle of incidence -1.6°. Perpendicular polarization.

Order m	Calculated A=1.02°, N=1.46138	Measured
+1	28.482±0.080	28.42±0.50
2	810.6±4.5	815±65
3	$(2.301 \pm 0.019) \times 10^4$	$(2.359 \pm 0.044) \times 10^4$
4	$(6.50 \pm 0.07) \times 10^5$	$(6.65 \pm 1.40) \times 10^5$

Table III

Fused silica beam splitter ratio of intensity of zeroeth order beam to beam of order m at 1.06 μm. Angle of incidence -1.0°. Unpolarized radiation.

Order m	Calculated A=1.02°, N=1.45268	Measured
-1	27.396±.068	27.396±.068
+1	29.361±.073	29.321±2.2
2	862.10±4.3	873.2±66
3	$(2.531\pm.019) \times 10^4$	$(2.562\pm.020) \times 10^4$
4	$(7.433\pm.074) \times 10^5$	$(7.454\pm.61) \times 10^5$

Table IV

Ratio of maximum to minimum transmittance due to interference in an absorbing plate.

Density	Max/Min
0.0	1.174
.1	1.136
.2	1.106
.3	1.084
.4	1.055
.5	1.052
.6	1.041
.7	1.032
.8	1.026
.9	1.020
1.0	1.016
1.1	1.013
1.2	1.010
1.3	1.008
1.4	1.005
1.5	1.005
1.6	1.004
1.7	1.003
1.8	1.003
1.9	1.002
2.0	1.002

Table V

Reflection correction for a filter of index n=1.50

Angle of Incidence (deg.)	Transmission Perpendicular	Transmission Parallel
1.0	.0000	-.0000
2.0	.0001	-.0001
3.0	.0003	-.0003
4.0	.0005	-.0005
5.0	.0009	-.0008
6.0	.0012	-.0012
7.0	.0017	-.0017
8.0	.0022	-.0022
9.0	.0028	-.0027
10.0	.0035	-.0034

Table VI

Tilt correction for a filter of index n=1.50.

Angle of Incidence (deg)	Filter Density .5	1.0	2.0	3.0
1.0	.0001	.0002	.0003	.0005
2.0	.0003	.0006	.0012	.0019
3.0	.0007	.0014	.0026	.0042
4.0	.0012	.0025	.0050	.0075
5.0	.0019	.0039	.0073	.0116
6.0	.0028	.0056	.0112	.0167
7.0	.0038	.0076	.0152	.0227
8.0	.0050	.0099	.0198	.0295
9.0	.0063	.0125	.0249	.0372
10.0	.0078	.0155	.0307	.0457

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15. SUPPLEMENTARY NOTES

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.*)

Some methods were investigated for the accurate attenuation of laser beams to very low levels; approximately 10^{-11} watts. This work was done at 1.06 and .6471 μm, but the conclusions are applicable throughout the visible region as well. Two types of devices were considered; wedged beam splitters and neutral density filters. The theory of the attenuation of a wedged beam splitter was described and some of the errors associated with these devices were discussed.

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*)

Beam splitter; laser attenuation; neutral density filter.

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