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WINDOWS AND MIRRORS NEEDED FOR A
LASER-DRIVEN PHOTONEUTRALIZER

J. H. Fink

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ABSTRACT

Rough estimates of the neutral fraction obtainable from a photoneutralizer and of the power required to operate it are presented as functions of the window and mirror performance. More precise information will become available in the future.

INTRODUCTION

The performance of a laser-driven photoneutralizer is a function of the quality of its windows and mirrors.¹ The higher the window transmission and the greater the mirror reflectivity, the smaller the optical losses. This, coupled with a suitably designed laser configuration, results in more intense illumination and, as a consequence, in an increased output of neutrals from an exposed negative-ion beam. However, an upper limit to the intensity is imposed by the maximum amount of continuous irradiation that the windows and mirrors can safely tolerate.

In the following, I use an oversimplified model of a photoneutralizer to estimate the effects of the real limitations of windows and mirrors. For instance, I have not used a Rigrod analysis,² and I considered scattering losses, absorption, and nonuniformity in the gain medium to be negligible. Although I do not address scattering or diffraction losses at the windows and mirrors specifically, I assume they are included in the effective window transparency T and mirror reflectivity R . This is a convenient though unrealistic approximation. Consider the mirror reflectivity for example. As defined above, it is not an intrinsic mirror property. It is a function of their number, spacing, and shape, as well as their absorption losses, surface polish, cleanliness, and the like. The results I obtain are useful nevertheless as they provide an approximation, as well as present the problem for future, more detailed analysis. More accurate studies, including details of the gain medium and optical system, will be done subsequently.

*On assignment from Nexion, Inc., Hayward, CA 94542.

PHOTONEUTRALIZER DESIGN

The photoneutralizer configuration under study is shown in Fig. 1. It includes a total of N mirrors, where N is an even number of mirrors, i.e., two or more. The laser gain medium of length l is enclosed by a back mirror of reflectivity R_0 and a front window of transmissivity T . The gain medium, which is composed of a mixture of excited oxygen, iodine, and a buffer gas (probably argon), is at a pressure of several torr. The region beyond the window, through which the negative ion beam travels, is at a pressure of about 10^{-6} torr. In this outer region, there are $N-1$ additional mirrors that reflect the light back and forth across the ion beam.

We can obtain an estimate of the laser gain needed to operate the photoneutralizer by following a light ray through the system. (A more rigorous analysis would use Rigrod's technique.)

If light leaves the gain medium with an irradiance ϕ (Wm^{-2}), it will be reflected from the first mirror with an irradiance of ϕR , with ϕR^2 from the second, with ϕR^3 from the third, and so on. Thus, with a system of N mirrors as shown, the light returning to the gain medium is ϕR^{2N-3} . Passing through the window, the irradiance of the light at point a is $\phi T R^{2N-3}$. At b, the light, having been enhanced by its travel through the length of the gain medium, is $\phi T R^{2N-3} e^{g l}$, where g is the small signal gain per unit length.

After being reflected at the back mirror, the light at point c is $\phi T R_0 R^{2N-3} e^{g l}$. Under continuous exposure to the active chemicals in the gain medium, we presume that reflectivity R_0 of the back mirror might not be as good as that of the other mirrors, which are mounted in the clean, low-pressure, ion-beam environment.

At d, the light is $\phi T R_0 R^{2N-3} e^{2g l}$ after traversing the gain medium once again. On the other side of the window, the light becomes $\phi T^2 R_0 R^{2N-3} e^{2g l}$. For sustained operation, the light leaving the window must equal ϕ , the value initially assumed. Thus, the gain of the laser has to be such that

$$T^2 R_0 R^{2N-3} e^{2g l} = 1 \quad (1)$$

Figure 1. Configuration of a laser-driven photoneutralizer.

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NEUTRAL FRACTION AND THE THICKNESS OF LIGHT

The neutral fraction obtained from a negative-ion beam passing through a photoneutralizer is a function of the ion-beam velocity v , the length L of the ion-beam path that is irradiated, the irradiance of the light ϕ , and the light frequency ν .

If the "thickness of light" through which the ion beam travels is defined as

$$S = \int_0^L \phi dz, \quad (2)$$

the neutral fraction becomes

$$\eta_N = [1 - \exp \{ - (\sigma/h\nu) S/v \}] , \quad (3)$$

where σ is the photodetachment cross section of light at the frequency ν .

Values of the thickness of light that are needed to provide different neutral fractions are shown in Fig. 2 as a function of the ion-beam energy for a deuterium beam exposed to light at a wavelength of 1.3 μm .

In a configuration similar to that shown in Fig. 1, the thickness of light through which an ion beam would pass is

$$S = N_S D \phi [1 + R + R^2 + \dots + R^{2N-3}] , \quad (4)$$

in which N_S is the number of such systems mounted in series along the ion beam path, and D is the width of the light beam in the direction parallel to the ion beam path.

Neglecting any space that might be left between adjacent mirrors, we find the length of a single system of N mirrors, as shown in Fig. 1, is

$$L = ND/2 . \quad (5)$$

Therefore, the total length of a neutralizer composed of N_S systems is

$$L_T = N_S ND/2 . \quad (6)$$

Figure 2. The optical thickness of a photoneutralizer delivering a neutral fraction.

An expression for the thickness of light of a given neutralizer is found by rearranging terms in Eq. (4) and introducing Eq. (6), whereby

$$S = \left(\frac{2L_T}{N} \right) \phi \left(\frac{1 - R^{2N-2}}{1 - R} \right). \quad (7)$$

If $\phi_w (\text{wm}^{-2})$ is the maximum total continuous irradiance the windows can tolerate, the irradiance ϕ , which leaves the laser gain medium as shown in Fig. 1, must be such that

$$\max \phi \leq \phi_w / (1 + R^{2N-3}). \quad (8)$$

Similarly, if $\phi_m (\text{wm}^{-2})$ is the maximum irradiance the mirrors can tolerate, then for $N > 2$, ϕ must be

$$\max \phi \leq \phi_m / (1 + R^{2N-2}). \quad (9)$$

For the geometry where $N = 2$, it can be seen that the total irradiance of the front mirror is lower than for $N > 2$. Thus

$$\max \phi \leq \phi_m. \quad (10)$$

Should the window tolerance for power loading be the limiting factor, the maximum thickness obtainable in a photoneutralizer can be found from Eqs. (7) and (8), i.e.,

$$\max S \leq 2L_T \phi_w \left[\frac{1 - R^{2N-2}}{N(1-R)(1+R^{2N-3})} \right]. \quad (11)$$

Should the mirror loading be the limiting factor for the case where $N > 2$, from Eqs. (7) and (9),

$$\max S = 2L_T \phi_m \left[\frac{1 - R^{2N-2}}{N(1-R)(1+R^{2N-4})} \right]. \quad (12)$$

For $N = 2$, from Eqs. (7) and (10),

$$\max S = \phi_m / (1 + R^2). \quad (13)$$

If we assume $R > 0.99$ and $N \leq 10$, the results of Eqs. (11), (12), and (13) are found to be insensitive to the actual value of R , and the differences between the results of Eqs. (11) and (12) are not significant. Hence, an estimate of the "optical thickness" obtainable from a 3-m-long neutralizer can be obtained from the curves shown in Fig. 3, provided the maximum tolerable irradiance of the windows and mirrors is known. From the maximum optical thickness established above, we can now estimate from Fig. 2 the maximum neutral fraction provided by the neutralizer.

OPTICAL POWER LOSS

In the photoneutralizer configuration shown in Fig. 1, the principal loss of light results from absorption and scattering at the window and absorption, scattering, and diffraction at the mirrors. Scattering and absorption in the gain medium is very small because the pressure in that region is so low, only a few torr. Meanwhile, the loss of light to the negative-ion beam is negligible because the ion-beam density is so low and the cross section for photodetachment is so small.

The loss of light to the $N-1$ external mirrors in a system of N_S sections, as shown in Fig. 1, is equal to the difference between the light leaving the gain medium and that returning to it, i.e.,

$$P_{EM} = N_S A_0 \phi (1 - R^{2N-3}), \quad (14)$$

where A_0 is the cross section of the light beam reflecting back and forth across the incident ion beam. I assume the light has the same cross section all along its path, but this is another simplifying approximation.

The power loss at the back mirror is

$$P_{BM} = N_S A_0 \phi (1 - R_0) T R^{2N-3} e^{g l}, \quad (15)$$

while the loss to the window from light passing out of and back into the gain medium is

$$P_W = N_S A_0 \phi (1 - T) (R^{2N-3} + T R_0 R^{2N-3} e^{2g l}). \quad (16)$$

Figure 3. The maximum optical thickness of a 3-m long photo-neutralizer as a function of the maximum tolerable irradiation on windows and mirrors.

Introducing Eq. (1) into the total optical loss, i.e., the sum of Eqs. (14), (15), and (16), results in

$$P_L = N_s A_0 \phi \left[T^{-1} - TR^{2N-3} + (1-R_0) \left(\frac{R^{2N-3}}{R_0} \right)^{1/2} \right] . \quad (17)$$

The optical power loss P_L in a photoneutralizer is, to the first approximation, proportional to the product of the optical thickness and the average neutralizer width, Y_A (in the "y" direction as shown in Fig. 1). By definition, the proportionality constant is the Q of the resonator. It represents the ratio of the optical power in the mirror cavity, to the cavity power loss. Because it is not exactly the usual definition of Q , I call it G , whereby

$$G = \frac{SY_A}{P_L} . \quad (18)$$

This is illustrated in Fig. 4 where, for various system designs, the optical power loss of a system whose average width is 4 cm is shown to be a function of G_e .

Estimates of G can be obtained from Eqs. (7), (17) and (18). If R_0 is assumed to equal R ,

$$G = \frac{(1 - R^{2N-2})}{(1-R) [T^{-1} - TR^{2N-3} + (1-R) R^{N-2}]} . \quad (19)$$

In Fig. 5 (a to e), I show G as a function of T , R , and N . For the case where T is one, G is approximately independent of N , whereby

$$G \approx \left(\frac{1}{1-R} \right) . \quad (20)$$

I should point out that the results presented here are just approximations. A more detailed study would show the effective mirror reflectivity to be a function of the number, shape, and spacing of the mirrors.

Figure 4. Optical power loss as a function of optical thickness for a beam of average width, $Y_A = 4 \times 10^{-2}$ m (which corresponds to an initial beam width of 1.5×10^{-2} m, a half-angle divergence of 0.5 deg, and a neutralizer length of 3 m). Factor G is defined in Eqs. 18 to 20 of the text.

Figure 5. The Factor G as a function of window transmissivity T and of mirror reflectivity R for N number of mirrors, see (a) to (e).

Dashed line ($T = 1.000$) is for $G \sim \frac{1}{1-R}$.

BEAM-LINE EFFICIENCY

The efficiency of a neutral-beam line is a function of the ratio of the power required to operate the neutralizer divided by the power of the output neutral beam. Obviously, photoneutralization makes a system more efficient if the power saved by obtaining an enhanced neutral fraction from an incident negative-ion beam is greater than the power expended to operate the improved neutralizer. It is not my intention to pursue this topic here. However, I do want to point out that the power required to operate the neutralizer, P_N , equals the optical power loss divided by the laser (wall-plug) efficiency ϵ_L . From Eq. (18),

$$P_N = \frac{S Y_A}{\epsilon_L G} \quad (21)$$

Unfortunately, the development of a suitable laser has not progressed far enough to establish the actual laser efficiency. We know it will be better than 2%. We hope it will be better than 6%.

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