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Hydrogen Fluoride vs Deuterium Fluoride Space-Based Laser Performance Comparison

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The on-orbit performances of hydrogen fluoride (HF) and deuterium fluoride (DF) lasers are compared. Only free-space propagation, without any atmospheric effects, has been considered in comparing the lethality, or brightness, of the two systems. An arbitrarily chosen set of residual values of wave front error, including both high and low spatial frequencies, and jitter are employed as degradation terms in calculating the brightness. Whereas conventional thinking is that shorter wavelengths are always better, this is not always the case when degradation terms are introduced. It is shown that the brightness of a DF laser beam is not reduced by the canonical factor of 2 from HF, i.e., by the ratio of wavelengths squared, as calculated without the effects of wave front error and jitter, but that it is equal to or greater than that of an HF laser (at equal power and primary mirror diameter) for the chosen set of degradation terms. Atmospheric propagation is presented as a separate issue, completely independent of the brightness, to show the greatly extended flexibility and lethality of DF over HF when engaging a target in the Earth's atmosphere. Also, the nozzle performance of HF and DF lasers are about equal and so their on-orbit volumes are equal and their weights are comparable, although the mode width of DF is about twice as long as that of HF, which reduces the intensity on the resonator optics by a factor of two and reduces the internal diffractive losses by about 30%.

Introduction

THIS paper details the differences and commonalities between a hydrogen fluoride (HF) space-based laser (SBL) operating at an average wavelength of 2.7 μm and a deuterium fluoride (DF) SBL operating at an average wavelength of 3.8 μm. HF and DF lasers are very similar in that one can become the other by simply swapping the combustor fuel with the cavity fuel. Of course, the optics must have the correct coatings to effectively reflect the chosen wavelength. An HF laser employs D_2 in the combustor, where it reacts with a fluorine-bearing oxidizer to produce atomic fluorine, and H_2 in the cavity, which then reacts with the atomic fluorine to produce excited HF to lase. A DF laser swaps the D_2 and the H_2 to produce and lase with excited DF.

The first section of the discussion compares the nozzle performance characteristics of both lasers. The nozzle performance is characterized by the nozzle power density (δ in watts per square centimeter), the specific efficiency (σ in kilojoules per kilogram), and the lasing mode width ($2x_c$ in centimeters) of the nozzle. The nozzle performance determines the size and weight of the SBL, as well as the loading on the resonator mirrors and the diffractive losses.

The second section compares the atmospheric transmittance capabilities of the two lasers. The transmittance through the atmosphere greatly enhances the utility of the DF laser over the HF laser. Whereas the HF laser cannot penetrate far into the atmosphere from space due to the high water absorption at the HF wavelengths, the DF laser possesses excellent propagation characteristics. Note that the atmospheric propagation in no way influences the brightness comparison presented in the next section, which is based solely on vacuum propagation.

The third section compares the brightness of the two SBLs. Brightness is a measure of the ability of a laser to concentrate power through a focusing mirror against those elements trying to disperse and/or degrade the beam [diffraction, wave front error (WFE), and jitter]. The brightness equation, which includes both high and low spatial frequency (SF) terms, as well as the optimum wavelength, which produces the highest brightness for any given choice of degradation terms, have been derived in a complementary paper by White[1] and are reproduced in this paper.

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Discussion

Nozzle Performance

The nozzle concept chosen for the HF/DF comparison is the hypersonic wedge nozzle (HWN), which is the nozzle presently employed on the Alpha laser. The HWN design is based on the technology developed under the Modular Army Demonstration System (MADS) program.[2] The MADS program included tests with DF/He and DF/N_2 lasant/diluent gas combinations. The HF/He data were obtained with the same nozzle hardware as the DF data under the laser scaling evaluation program (LSEP)[2] on the MADS device. These two test series, thus, provide a database for the comparison of HF vs DF performance with the same nozzle, on the same device, under the same operational conditions.

The various data from the MADS and LSEP programs were compiled, reduced, and compared,[2] and the results are presented in Figs. 1 and 2 for the helium diluent test series. Figure 1 indicates the constancy of performance as the cavity fuel R_L is increased above a critical value of around 8, therefore showing that the HF/He data are basically an extrapolation and continuation of the DF/He data. Our models, likewise, show that both the DF and the HF performance values are basically the same for the same conditions, as shown in Fig. 1.

The effect of lasing mode width on closed cavity performance is presented in Fig. 2. The data show an optimum mode width of about 2.6 cm for HF/He and an extrapolated mode width of 5 cm for DF/He. Figure 2 includes both the MADS/LSEP data and our wave optics analyses. The correlation between the analyses and the data is excellent and shows clearly the factor of two increase in the DF mode width over the HF. This doubling in the mode width results in two very important positive attributes for DF over HF. The first is that the intensity on the DF resonator optics is half of the intensity on the HF optics, which is extremely important for the highly loaded, uncooled optics of a high-power SBL. This optical intensity could very likely be the limiting factor on the power capability of an SBL. The tremendous advantage of being able to halve this limiting intensity is obvious. The second is that the diffraction loss in the resonator (internal diffraction) is reduced by approximately 30% for DF over HF. This results from the fact that diffraction goes as $\lambda/2x_c$ and although λ increases from 2.7 to 3.8 μm, the mode width $2x_c$ increases by a factor of two, with the net result that the internal DF diffraction is 70% of the internal HF diffraction.

Figures 1 and 2 show the closed cavity nozzle power density δ_{cc} (watts per square centimeter) in a normalized fashion to keep

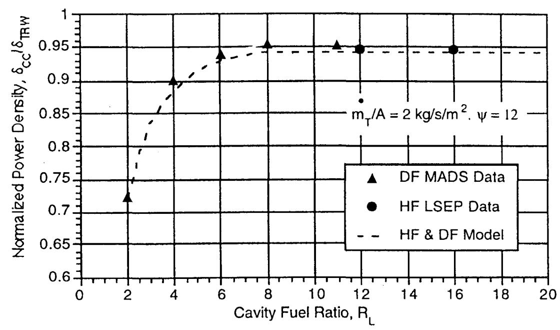

Fig. 1 Performance comparison between DF and HF lasing.

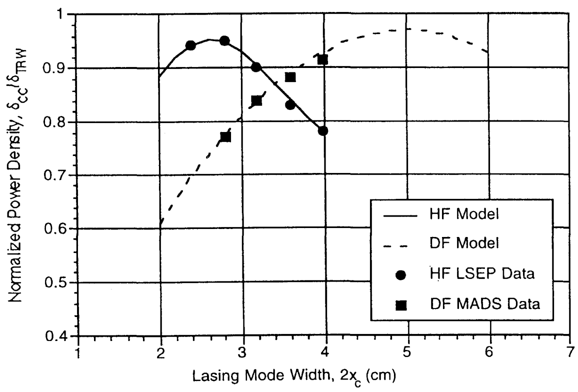

Fig. 2 Comparison of DF and HF lasing mode width.

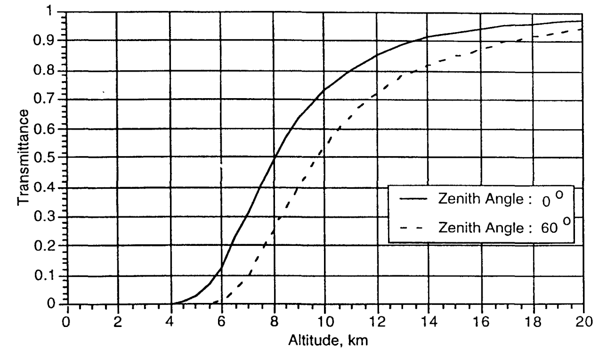

Fig. 3 HF laser transmittance from space to atmosphere.

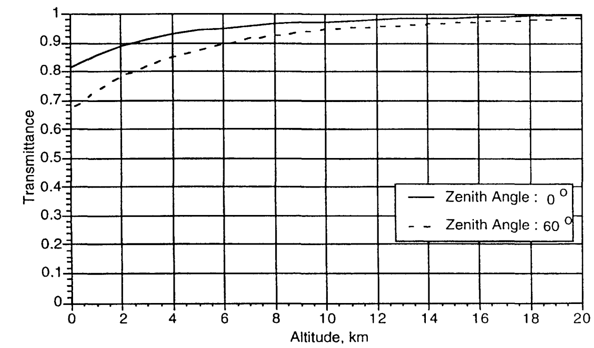

Fig. 4 DF laser transmittance from space to atmosphere.

the results unclassified. The normalizing factor δ_{TRW} is the one employed by TRW. Here, δ is based on the nozzle face area and is, thus, indicative of the size and weight of the laser device without the fluid supply system. The equal δ for HF and DF, shown in Figs. 1 and 2, represent equal power output from equal nozzle areas and, thus, equal size devices. The companion performance indicator to the power density is the specific efficiency σ_{cc} (kilowatts per kilogram per second), which is indicative of the size and weight of the fluid supply system. Note that σ_{cc} has not been included here but only differs between HF and DF due to the weight difference between H_2 and D_2. The molar swap of H_2 for D_2 introduces a slight reduction in σ_{cc} and, therefore, a slight weight penalty on the DF system because a larger amount of cavity fuel is carried onboard than combustor fuel and because D_2 weighs twice as much as H_2 per mole. Figure 1 indicates that the cavity fuel ratio ($R_L \sim 2 \times$ moles of cavity fuel/mole of F) needs to be >8 for maximum performance, whereas the combustor fuel ratio needs to be <1 to operate oxidizer rich to produce excess fluorine. For the nominal Alpha-type operating conditions, this fuel swap results in less than a 4% increase in the DF SBL system weight over the HF system weight at equal powers and equal beam directors.

Atmospheric Transmittance

Whereas the brightness determines the free-space performance capabilities of these two laser types, the transmittance through the atmosphere greatly enhances the utility of the DF laser over the HF laser. By its very definition, the transmittance only includes those terms that rob power from the beam, such as absorption and scattering, and does not include thermal blooming and turbulence, which distort and spread the beam but maintain the power. Limited analyses have hinted that, for our case of transmission from space to the atmosphere, the thermal blooming acts as a focusing lens instead of a defocusing lens as is the norm for ground- or air-based operation. A DF SBL opens up a whole new spectrum of target opportunities not available to the HF SBL. The ability to propagate through the atmosphere from space significantly broadens the lethal sphere of influence of the SBL to provide air superiority in theater engagements by engaging and destroying air breathing targets such as cruise missiles and aircraft, to acquire theater and strategic ballistic missiles earlier in their boost phase instead of having to wait until they clear the cloud tops or higher, and to reach the ground with lethal fluence and destroy ground-based/grounded weapon systems, etc.

We have performed detailed analyses, based on atmospheric data, of the space-to-atmosphere propagation capabilities of various directed energy weapon concepts.[3] These concepts have included neutral particle beam weapons, single-pulse and repetitively pulsed excimer lasers, induction and rf linear accelerator free electron lasers, chemical oxygen iodine lasers (COIL), and DF, HF, and HF overtone lasers. A modified midlatitude summer atmosphere was chosen for this study with a water partial pressure of 9.325 torr and 50% relative humidity at sea level. The water partial pressure in the atmosphere can range from 3 torr (dry winter conditions) to 20 torr (tropical conditions).

The results of this propagation study[3] for laser transmittance from space to the atmosphere at two zenith angles (0 deg = vertical and 60 deg) are presented in Figs. 3 and 4 for HF and DF, respectively. These results are for the transmittance of the average laser beam, which is made up of all of the applicable lasing lines. The high-saturation Alpha spectrum was used for the HF propagation, and the high-saturation midinfrared advanced chemical laser (MIRACL) spectrum was used for the DF propagation.

The inability of HF to penetrate far into the atmosphere from space is apparent from Fig. 3, where it can be seen that 25% of the beam has been dissipated by the time it reaches the cloud tops, i.e., 10 km or 35,000 ft, and that no penetration occurs below about 5 km. This is due to the high water absorption at the HF wavelengths. The fact that 25% of the HF beam is lost by the time it reaches the cloud tops is in direct contradiction to the popular belief that the HF beam remains reasonably intact down to this altitude. The DF beam, on the other hand, has excellent propagation characteristics, being hardly affected at 10 km (losing only 2.5% of its power) and propagating all the way to the ground with minimal losses (18%), as shown in Fig. 4. The loss numbers just quoted are for a direct space-to-ground propagation path (0-deg zenith angle). If the zenith angle is increased to 60 deg, the losses nearly double in every instance, as shown in Figs. 3 and 4. This means that, at a 60-deg zenith angle, the HF beam has lost nearly $\frac{1}{2}$ of its power by the time it reaches the cloud tops.

The exemplary propagation characteristics of DF are obvious when compared to the U.S. Air Force's theater missile defense air-based laser option, COIL, operating at 1.315 μm, which was chosen mainly for its excellent atmospheric propagation. COIL has slightly higher beam losses from space to ground (24%) than does DF (18%) for the atmospheric conditions used in this paper.

Lethality

Brightness B is the primary lethality figure of merit, which has been chosen by the laser community to compare SBLs. Brightness is a measure of the ability of a laser to concentrate power through a focusing mirror against those elements trying to disperse and/or degrade the beam (diffraction, WFE, and jitter). Brightness is not dependent on range and is expressed simply as power per unit solid angle of beam spread (watts per steradian). Two terms representative of residual wavefront error, which reduce brightness, have been used in this paper. The first is β_L, a low SF WFE that spreads the beam; the second is β_H, a high SF WFE that reduces the power on target without affecting the beam spread. Either term, or a combination of both terms, may be used depending on one's perception of the residual WFE. This residual error, though, is expected to be primarily composed of high SF terms because the low SF terms are the ones mostly eliminated by the correcting optics such as the deformable mirror and the fast steering mirror employed in SBLs.

White[1] states that "Since the beam control system has a much greater error rejection at low spatial (and temporal) frequencies, the most likely residual error is one that is predominately high spatial frequencies." Because of this, the residual wavefront error in this paper has been arbitrarily interpreted as being made up of 20% low and 80% high SF terms. A bonafide lethality comparison can, therefore, be made between HF and DF lasers by comparing the brightness of both systems for equal degradation factors, i.e., equal amounts of residual optical path differences (OPDs) and equal levels of residual jitter. The completely general brightness equation used, which includes both high and low SF terms, has been derived in detail in the complementary paper[1] and is given by

$$B = \frac{P}{2\pi\beta_H^2\left(\beta_L^2\sigma_{D_x}^2 + \sigma_x^2\right)} \tag{1}$$

where

$D(m)$ = primary mirror diameter
$P(W)$ = power out of primary mirror
β_H^2 = high SF WFE, $\exp(2\pi\delta_H/\lambda)^2$
β_L^2 = low SF WFE, $1 + (2\pi\delta_L/\lambda)^2$
δ = rms OPD, $\surd(\mathrm{OPD}_{\mathrm{Dev}}^2 + \mathrm{OPD}_{\mathrm{BCS}}^2)$
σ_{D_x} = single axis diffraction, $\surd 2\lambda/(\pi D)$
σ_x = single axis jitter

resulting in

$$B = \frac{P\exp\left[-(2\pi\delta_H/\lambda)^2\right]}{\pi\left\{\left[1 + (2\pi\delta_L/\lambda)^2\right][2\lambda/\pi D]^2 + 2\sigma_x^2\right\}} \tag{2}$$

The rms OPD presented, δ, is composed of the OPD degradations from the laser device $\mathrm{OPD}_{\mathrm{Dev}}$, which produce the beam (includes the flowfield and optical resonator), and from the beam control system $\mathrm{OPD}_{\mathrm{BCS}}$, which collect and expand the beam to fill the large primary optic that directs it to the target. These two terms, $\mathrm{OPD}_{\mathrm{Dev}}$ and $\mathrm{OPD}_{\mathrm{BCS}}$, therefore, account for all of the WFE degradations in the beam train. This total WFE can then be appropriated into high δ_H and low δ_L SF terms. These terms, in conjunction with the jitter and diffraction, completely characterize the system. The jitter and diffraction numbers employed are the commonly used single-axis values. If one wishes to use the two-axis values, or the line-of-sight values, the following transformation can be easily applied and replaced in Eq. (1).

Diffraction:

$$\sigma_D \text{ (line of sight)} = \sqrt{2}\sigma_{D_x} \text{ (single axis)}$$

Jitter:

$$\sigma \text{ (line of sight)} = \sqrt{2}\sigma_x \text{(single axis)}$$

The results are obviously the same as long as the values input are consistent with the brightness equation employed. The effect of jitter on brightness is directly dependent on the diffraction $\surd 2\lambda/(\pi D)$ and the amount and distribution of the WFE (δ_H and δ_L) per Eq. (2), and the total beam spread (steradiancy) is given by the denominator of Eq. (1). The brightness of the system, thus, can be measured by measuring the OPDs and the jitter of the system without having to measure the actual beam in either the near or the far field.

The following parameters have been arbitrarily chosen in order to compare the brightness of the two systems:

$$\mathrm{OPD}_{\mathrm{Dev}} = 0.33\,\mu\mathrm{m}, \qquad \mathrm{OPD}_{\mathrm{BCS}} = 0.33\,\mu\mathrm{m}$$

$$\sigma_x = 0.33\,\mu\mathrm{rad}, \qquad \delta_H = 0.8 \times \delta, \qquad \delta_L = 0.2 \times \delta$$

A lethality comparison between HF and DF, thus, can be made by using the parameters just listed, with the average wavelength values for HF ($\lambda_{\mathrm{HF}} = 2.7\,\mu$m) and DF ($\lambda_{\mathrm{DF}} = 3.8\,\mu$m), in Eq. (2). If the ratio of the brightness of DF to HF is used for the comparison, $B_{\mathrm{DF}}/B_{\mathrm{HF}}$, then the primary mirror diameter D is the only unknown left to be identified because the power P is assumed equal for both and, therefore, cancels from the ratio. Therefore, the brightness ratio for $D = 4$ m is calculated to be

$$B_{\mathrm{DF}}/B_{\mathrm{HF}} = 1.00$$

and for $D = 8$ m

$$B_{\mathrm{DF}}/B_{\mathrm{HF}} = 1.24$$

These results show that, for the beam degradation factors and the high-to-low SF ratio chosen, the brightness of a DF SBL is equal to that of an HF SBL for $D = 4$ m and becomes significantly greater than that of an HF SBL (24%) as the primary mirror diameter is increased from 4 to 8 m.

To note the overall effect of wavelength on brightness, as the mix of high-to-low SF is changed, the brightness relationship (2) has been exercised over a broad range of wavelengths for the following three scenarios.

All high SF:

$$\delta_H = \delta, \qquad \delta_L = 0.0$$

All low SF:

$$\delta_H = 0.0, \qquad \delta_L = \delta$$

SF mix used:

$$\delta_H = 0.8 \times \delta, \qquad \delta_L = 0.2 \times \delta$$

The results are shown in Figs. 5 and 6 for $D = 4$ m and $D = 8$ m, respectively. The contrary behavior of brightness, based on high SF vs low SF, as wavelength is decreased from some arbitrary high value, where they are both equal, is apparent from Figs. 5 and 6. The brightness composed only of low SF terms continuously increases as the wavelength is decreased, which is the normally expected behavior, whereas the one composed of high SF terms produces an optimum and then decreases to zero, which is the unexpected but

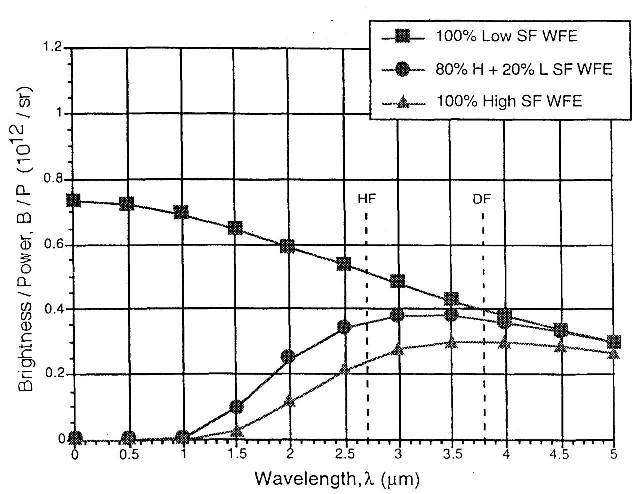

Fig. 5 Effect of wavelength and SF for D = 4 m.

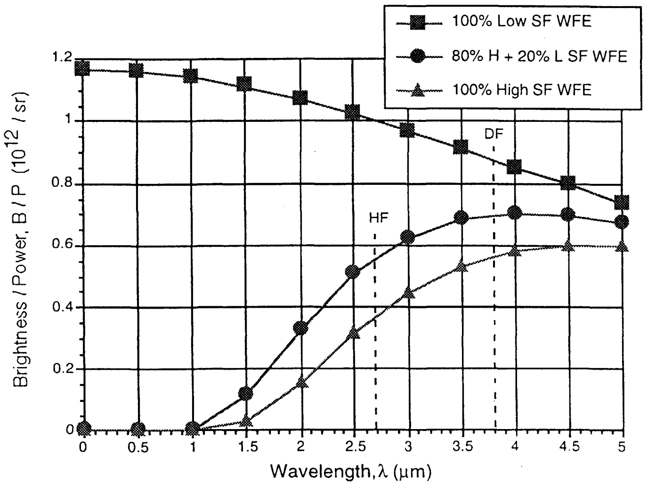

Fig. 6 Effect of wavelength and SF for D = 8 m.

correct result when high SF degradations are employed. The optimum brightness value shown in these figures can be easily calculated by taking the derivative of the brightness [Eq. (2)] with respect to λ and setting the result equal to zero. This was performed by White,[1] and the result is

$$\lambda_{\text{opt}} = \sqrt{2}\pi\delta_H\sqrt{1+\sqrt{1+\frac{8\delta_L^2+\sigma_x^2D^2}{2\delta_H^2}}} \tag{3}$$

For the chosen mix of high (80%) and low (20%) SFs used, one can see from Fig. 5 that for $D=4$ m the brightness of the HF and the DF are equal, with the optimum brightness, obtained from Eq. (3), occurring at 3.24 μm. For $D=8$ m, Fig. 6 shows, and Eq. (3) predicts, that the optimum wavelength is 4.14 μm, which favors wavelengths even higher than that of DF.

Conclusions

This paper provides a completely general relationship (2) for comparing the brightness and, thus, the power on target of SBLs operating with degradations attributed to residual beam jitter and residual WFE containing both high and low SFs. Whereas conventional wisdom seems to indicate that shorter wavelengths are the most desirable for space-based applications, this paper has decisively shown that this is not always the case. For the chosen set of degradation terms used here, the brightness of a DF laser beam is equal to (for $D=4$ m) or greater than (by 24% for $D=8$ m) that of an HF laser beam. The optimum wavelength for an SBL is a function of the magnitude of the degradation factors as well as the high-to-low SF allocation.

Both the HF and the DF laser, based on the measured HWN data presented here, have basically the same nozzle performance at comparable conditions resulting in equal system volumes and near equivalent system weights. There is, however, a slight weight penalty for the DF system because a larger amount of cavity fuel is carried onboard than combustor fuel and because D_2 weighs twice as much as H_2 per mole. Also, the optimum mode width for DF is about twice as long as for HF, resulting in one-half of the intensity loading on the DF annular resonator optics as well as a 30% reduction in the internal diffractive losses.

Whereas the brightness determines the free-space performance capabilities of these two laser types, the transmittance through the atmosphere greatly enhances the utility of the DF laser over the HF laser. A DF SBL opens up a whole new spectrum of target opportunities not available to the HF laser. An HF laser beam loses about 25% of its power by the time it reaches the cloud tops (10 km) from space (45% loss at a zenith angle of 60 deg) and can never reach the ground. This corrects the misconception that the HF beam reaches the cloud tops unscathed. DF lasing, on the other hand, provides excellent atmospheric penetration from space (only 2.5% loss to 10 km and 18% loss to the ground) and significantly broadens the SBL's lethal sphere of influence to engage and destroy air breathing targets, such as cruise missiles and aircraft, as well as ground-based and/or grounded targets.

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