Continuously variable distortion-free attenuation of high-power transversely excited atmospheric CO_2 laser pulses

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A new technique for the continuously variable linear attenuation of high-power transversely excited atmospheric (TEA) CO_2 laser pulses is reported. The use of a binary gas mixture comprising SF_6 as the absorber and helium or argon as the buffer gas causes a significant enhancement in the saturation intensity, thereby allowing saturation-free attenuation of TEA CO_2 laser pulses up to 1 MW/cm^2. A linearly variable dynamic attenuation range of 0–30 dB, and continuously variable attenuation up to 60 dB in a 10-cm cell length, without spatial or temporal distortion in the attenuated beam is demonstrated.

I. INTRODUCTION

Precise attenuation of high-power pulsed CO_2 laser radiation without spatial or temporal distortion is important in many applications ranging from micromachining to threshold measurements. Attenuation methods using Brewster stacks, gratings, or frustrated internal reflection rely on the polarization of the incident laser radiation.[1] On the other hand, the use of absorbing flats (such as CaF_2 or LiF) allows only discrete attenuation. An additional disadvantage of such techniques is the lack of ready scalability to large aperture, high-energy laser beams. A possible solution to these drawbacks is the use of gas attenuators.[1–3] However, for a large dynamic attenuation range over reasonable path lengths, the requirement of a suitably large absorption cross section inevitably leads to saturation and consequent beam distortion at relatively moderate laser intensities.

We report, in this article, the basic concept and experimental details of a novel attenuation approach that uses a binary mixture of an absorber gas and a buffer gas to overcome the limitation of low saturation intensity. The experiments reported in this article were performed using the 10.6 μm [10P(20) CO_2 laser transition] output of a TEA CO_2 laser. SF_6 was used as the gaseous absorber for the attenuator. Though desirable for the attenuation of 10.6-μm laser radiation because of a high absorption cross section ($\sigma = 1.6 \times 10^{-17}$ cm^2), SF_6 has been known to saturate readily. In fact, the saturation of SF_6 has been used for mode-locking CO_2 lasers.[4] The nanosecond pulse transmission of buffered SF_6 for saturable absorber applications in the high intensity regime has been studied.[5] We demonstrate that the addition of a buffer gas significantly enhances the saturation intensity due to rapid depopulation of the upper state. Comparative attenuation data obtained for two buffer gases, helium and argon, elucidate the role of collision frequency in enhancing the saturation intensity of the absorber. Continuous tunability of attenuation is demonstrated, in the 0–60-dB range, as a function of absorber gas pressure in the binary mixture. A study of possible spatial and temporal beam distortion in the attenuated laser pulse is also presented.

II. THEORETICAL BACKGROUND

Any gas attenuator relies on a Beer's law absorption in the gas cell to alter the energy of the transmitted laser pulse with the transmission

$$T = \exp[-\alpha l], \quad (1)$$

where l is the absorption length and α the absorption coefficient of the gas given by

$$\alpha = N\sigma, \quad (2)$$

where N is the number density of the absorber molecules and σ the absorption cross section.

For polyatomic absorbers, absorbing at line center, a characteristic Doppler-broadened regime at lower pressures (with linearly increasing α as a function of pressure) gives way to the pressure-broadened regime for which α is independent of pressure. For example, the experimentally measured absorption of 10.6 μm laser radiation by CO_2 exhibits this trend with nonlinearly changing α as a function of pressure between 0.9 and 20 Torr.[6]

The desirable requirement of linear attenuation as a function of absorber pressure would appear to indicate the Doppler-broadened regime as the operational range of choice. There are, however, two compelling reasons not to operate any variable attenuator in this regime. The first problem associated with operating at low pressures is a reduction of N and consequently α. This compromises the maximum possible attenuation for a given absorber length. Clearly, this problem may be circumvented by increasing the absorber length. However, for most practical applications, experimental constraints place upper limits on available absorber length. A more serious impediment to distortion-free attenuation in the Doppler-broadened regime is the low saturation intensity characteristic of the low pressures required for operation in this regime.

The absorption of laser radiation by large polyatomic molecules may be described as multiple two-level absorptions corresponding to photon interaction with a density of

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states resulting from the superposition of 3N−6 anharmonic vibrational sets of energy levels for an N-atom molecule. For the pressure broadened regime, each two-level absorption with a homogeneously broadened absorption linewidth implies an absorption cross section (σ) dependent on the incident laser intensity (I) such that

$$\sigma(I)=\frac{\sigma_0}{(1+I/I_s)}, \quad (3)$$

where σ_0 is the small-signal (unsaturated) absorption cross section and I_s the saturation intensity (at which σ is reduced to $\sigma_0/2$). In analogy with atomic systems, for pulsed radiation with pulse duration greater than the collisional deactivation time (τ) of the upper state, the saturation intensity may be represented by[7]

$$I_s(\nu)=\frac{8\pi n^2 h\nu t_s}{\tau\lambda^2 g(\nu)}, \quad (4)$$

where n is the refractive index of the gas, $h\nu$ is the photon energy, t_s is the spontaneous lifetime of the upper state, λ is the laser wavelength, and $g(\nu)$ is the Lorentzian absorption line shape function.

At absorption line center (i.e., when the laser frequency ν, is in resonance with the molecular absorption of width $\Delta\nu$ centered at ν_0),

$$g(\nu_0)=\frac{2}{\pi\Delta\nu} \quad (5)$$

and

$$I_s(\nu_0)=\frac{4\pi^2 n^2 h\nu_0 t_s \Delta\nu}{\tau\lambda^2}. \quad (6)$$

The pressure dependence of I_s is readily determined as

$$\tau \propto P^{-1} \quad \text{and} \quad \Delta\nu \propto P, \quad (7)$$

which implies

$$I_s(\nu_0) \propto P^2. \quad (8)$$

To obtain a high saturation intensity, it is therefore expedient to operate the gas attenuator at high pressure.

Even though the pressure-broadened regime affords the advantage of higher saturation intensity, controlling the variability of attenuation using the gas pressure in this regime is problematic since the absorption coefficient at higher pressures is independent of pressure ($N \propto P$ and $\sigma \propto P^{-1}$, causing $\alpha = N\sigma$ to be pressure independent).

A novel technique to overcome this obstacle, while retaining the lack of saturation advantage afforded by high-pressure attenuator operation, is the use of a buffer gas in conjunction with the absorber. The basic physical principle relies on the fact that saturation intensity depends on total gas pressure, while attenuation relies on the number density of absorbing molecules alone. Therefore, by keeping the total gas pressure of the binary mixture at a constantly high value while varying the partial pressure of the absorber gas, variably controlled saturation-free attenuation of high-power laser pulses is realized.

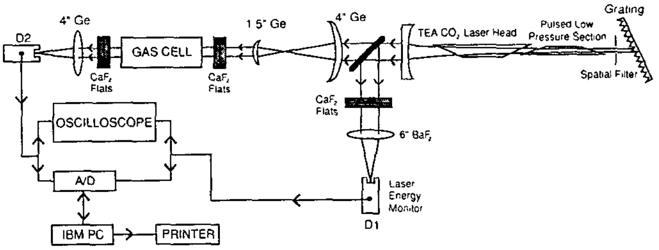

FIG. 1. Optical layout and data acquisition system.

III. EXPERIMENTAL DETAILS

The requirement of a binary gas mixture for the attenuator necessitated the use of a circulator for mixing the absorbing and buffer gases effectively in the gas cell. In addition to expeditious mixing, it was observed that flowing the mixture during the attenuation operation yielded consistently stable attenuated laser output.

The experimental system used to obtain the attenuation data is shown in Fig. 1. The 10.6 μm laser output was obtained as a gain-switched pulse from a grating-tuned TEA CO_2 laser system, incorporating a pulsed low-pressure section for single longitudinal mode operation. The cavity length was controlled by a piezoelectric transducer for mode selection. An intracavity spatial filter ensured TEM_{00} operation, providing a Gaussian spatial profile. The use of a 1:1:7 (N_2:CO_2:He) mixture generated laser pulses of ~80 ns FWHM with approximately 50% of the energy in the gain-switched portion of the pulse.

A 90/10 germanium beamsplitter at the output of the TEA CO_2 laser system diverted a small portion of the laser pulse for monitoring shot-to-shot fluctuations, using a pyroelectric detector ($D1$). The major portion of the CO_2 laser pulse was collimated without astigmatism using a 4″/1.5″ telescopic system (comprising AR-coated Ge lenses) and was then incident on the gas attenuator. The spatial profile of the laser beam, measured at the entrance to the gas cell, exhibited a Gaussian intensity distribution with a FWHM of ~2 mm.

The laser energy was suitably attenuated prior to incidence on the gas cell, using calibrated CaF_2 flats. The outputs of the two pyroelectric detectors ($D1$ and $D2$) were displayed on an oscilloscope while being simultaneously digitized and stored on an IBM PC for data analysis. Transmitted pulse energy measurements, with and without the gas in the cell, were normalized to eliminate laser energy fluctuations and used to accurately measure the effective transmission (T) of the absorber gas. The gas cell attenuation A (in dB) may be simply calculated as

$$A=-10\log(T), \quad (9)$$

where T is related to the absorption cross section (σ) through Eqs. (1) and (2).

IV. RESULTS AND DISCUSSION

The following results describe the performance of the binary gas attenuator for 80 ns FWHM TEA CO_2 laser pulses at 10.59 μm.

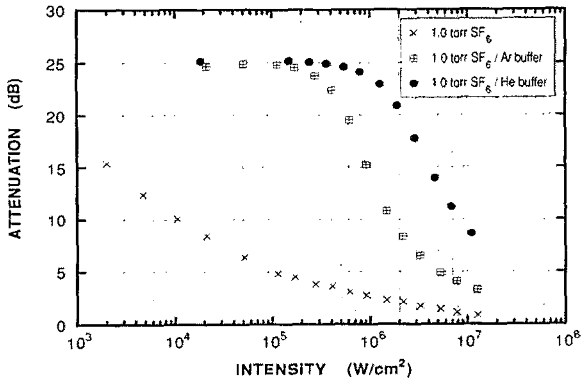

FIG. 2. Laser pulse attenuation as a function of peak input laser intensity for 1.0-Torr SF_6 in SF_6/Ar and SF_6/He mixtures at a total pressure of 760 Torr in each case. The absorption for 1.0 Torr of SF_6 without the buffer gas is included for comparison.

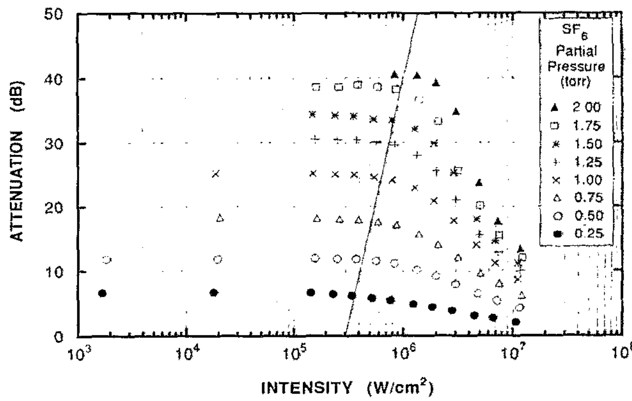

FIG. 3. Absorption characteristics for eight different SF_6 partial pressures. The total pressure of the SF_6/He binary mixture is 760 Torr in each case.

A. Saturation characteristics of the gas attenuator

The crosses in Fig. 2 depict the result obtained for the absorption characteristics of 1.0 Torr of SF_6 without any buffer gas. Severe saturation (i.e., decrease in attenuation as a function of increasing laser intensity) is clearly indicated even at the lowest laser intensity of 2 kW/cm^2. The advantage of a buffer gas in increasing the saturation intensity is shown in the absorption characteristics of Fig. 2 for 1.0 Torr of SF_6 in a background pressure of 759 Torr of argon. The constancy of the attenuation (at 25 dB) as a function of intensity up to 100 kW/cm^2 is obvious.

There are two parameters of interest in the analysis of saturation effects. The first is the saturation intensity (I_s), while the second is the laser intensity for the onset of saturation. In the pressure-broadened regime, which is applicable to our experimental case including the buffer gas, the saturation intensity may be defined by

$$A=\frac{A_0}{1+I/I_s}, \tag{10}$$

where A is the attenuation (in dB) at a laser intensity I and A_0 is the unsaturated (low intensity) value of the attenuation (in dB). Using this definition, the measured saturation intensity (from Fig. 2), of 4.5 kW/cm^2 without the buffer gas (at 1.0 Torr of SF_6) is elevated to $\sim$1.1 MW/cm^2 in the presence of the argon buffer—an increase of over two orders of magnitude. However, in terms of applicability as an attenuator, it is perhaps more relevant to consider the laser intensity for the onset of saturation. This is the intensity at which a departure from the small-signal attenuation occurs. The onset of saturation with the argon buffer is at $\sim$100 kW/cm^2.

A further improvement in saturation intensity using helium as the buffer gas is also shown in Fig. 2. The solid dots in the figure represent the absorption characteristic of 1.0 Torr partial pressure of SF_6 in a background of 759 Torr of helium. The saturation intensity using the helium buffer is $\sim$5.5 MW/cm^2 in comparison with the 1.1 MW/cm^2 obtained for the SF_6/Ar binary mixture. This represents a further fivefold increase in saturation intensity. The onset of saturation is also elevated to $\sim$400 kW/cm^2 with the He buffer in comparison to 100 kW/cm^2 for its Ar counterpart. Figure 2 indicates the general efficacy of a buffer gas for enhancing the saturation intensity and suggests helium as the preferred buffer (in comparison with argon). The increased saturation intensity for helium is consistent with an increased collisional deactivation rate of the absorbing SF_6 molecules by the lighter helium atoms.

The variation of attenuation with incident peak laser intensity at eight different partial pressures of SF_6 is presented in Fig. 3. In each case, the buffer gas is helium and the total pressure (buffer + SF_6) is 760 Torr. In addition to the general demonstration of tunability of attenuation as a function of SF_6 partial pressure, Fig. 3 indicates a saturation intensity of $\sim$5.5 MW/cm^2, independent of SF_6 partial pressure. This is consistent with the physical argument that the saturation intensity is primarily a function of total pressure, which is invariant for all eight curves in Fig. 3. Of course, the nature of the buffer gas also influences the saturation intensity, as shown earlier in Fig. 2.

The laser intensity for the onset of saturation is observed to increase with increasing SF_6 partial pressure. The solid inclined line in Fig. 3 is an approximate demarcation between the unsaturated regime (to its left) and the regime showing saturation effects (to its right). The intersection of the solid line with the x axis yields a minimum value of 300 kW/cm^2 (at the 0 dB limit) for the onset of saturation. At higher attenuations, the onset of saturation is at much higher laser intensities. For example, at 40 dB operation of the gas attenuator, the onset of saturation occurs at $\sim$1 MW/cm^2. However, significantly, even for the lowest attenuation measured, there is no hint of saturation up to 300 kW/cm^2.

B. Unsaturated attenuation characteristics

The unsaturated region to the left of the oblique line in Fig. 3 is of greatest operational interest for the SF_6/He binary gas attenuator. In addition to not being saturated, the attenuator must be capable of variable attenuation. In our binary gas attenuator, this is *easily* accomplished by varying the partial pressure of the absorber gas (SF_6)

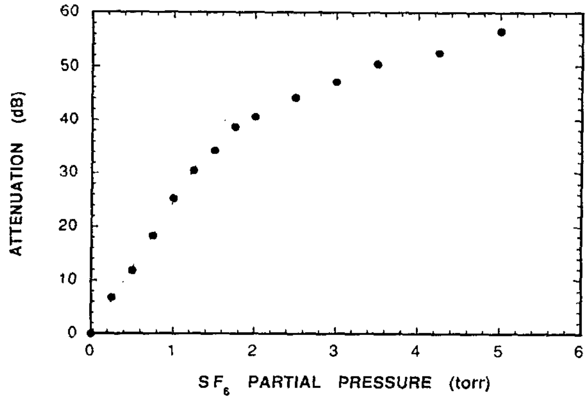

FIG. 4. Attenuation of the laser pulse as a function of SF_6 partial pressure in a 760-Torr SF_6/He binary mixture demonstrating continuous variability of attenuation in the 0–60-dB range. The solid line indicates linear attenuation up to 31 dB.

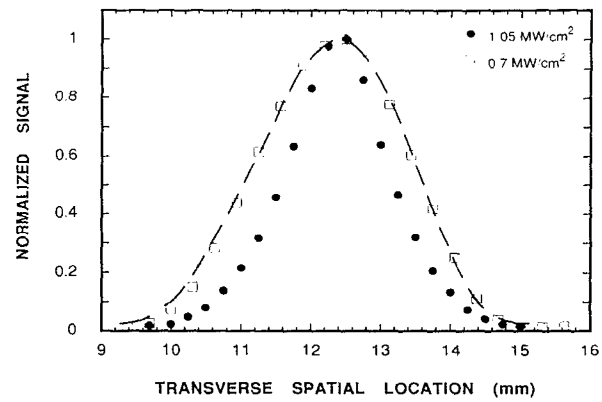

FIG. 5. Comparison of the normalized spatial profiles for the attenuated beam at an input laser intensity of 80 kW/cm^2 (shown by the dashed line) to that at 0.7 MW/cm^2 and 1.05 MW/cm^2. The attenuator was 0.5 Torr of SF_6 in a 760-Torr SF_6/He binary mixture for all the profiles.

while compensating the buffer gas (He) to maintain a total pressure of 1 atm in the attenuator.

A plot of attenuation (in dB) as a function of SF_6 partial pressure is shown in Fig. 4. In the 0–30-dB range, a linear increase in attenuation with SF_6 partial pressure is observed. A least-squares fit to the experimental data, indicated by the solid line, yields a 24.6 dB attenuation per Torr of SF_6 for the 10.17-cm experimental cell.

Further attenuation is possible by increasing the SF_6 partial pressure. However, at partial pressures greater than ~1.25 Torr, the linear relationship evidenced up to ~31 dB is not preserved. This is also shown in Fig. 4 where attenuation close to 60 dB is observed at 5 Torr SF_6 partial pressure. The significant result is that the attenuation has not flattened out even at ~60 dB and higher attenuations (exceeding 60 dB) are possible, merely by increasing the partial pressure of SF_6 above 5 Torr.

C. Beam distortion characteristics

An essential feature of a laser pulse attenuator is the prevention of spatial, temporal, and phase distortions in the attenuated laser beam. Beam modification, leading to distortion, is anticipated in the event of absorption saturation. The previous data monitored the effects of saturation exclusively by observing the absorption characteristics. We now discuss results obtained on the direct measurement of spatial and temporal profiles of the attenuated beam.

The spatial integrity of the laser beam was investigated by acquiring transverse spatial profiles of the attenuated laser beam, after passage through the gas attenuator. Spatial profiles were obtained at different values of incident laser intensity for a partial pressure of 0.5 Torr of SF_6 in the attenuator at a total gas pressure (including the He buffer) of 1 atm (represented by the open circles in Fig. 3). As a representative example, the spatial profile of the attenuated beam obtained subsequent to the onset of saturation, at a laser intensity of 0.7 MW/cm^2, reveals no noticeable beam modification from the unsaturated low intensity spatial profile (see Fig. 5). At a laser intensity of 1.05 MW/cm^2, however, a spatial narrowing of the attenuated beam is observed (Fig. 5). This is expected, as saturation of absorption preferentially transmits the central (higher intensity) portion of the beam in comparison to the lower intensity wings.

Similar results were obtained on using a fast detector to observe the temporal profile of the attenuated beam. At laser intensities less than 0.7 MW/cm^2 (for a partial pressure of 0.5 Torr SF_6) no alteration in temporal intensity was observed. For intensities exhibiting significant saturation, the low intensity "tail" of the TEA CO_2 laser pulse was heavily attenuated. No significant narrowing of the ~80 ns FWHM of the TEA pulse was observed. No beam deflection or additional divergence was observed in the attenuated laser beam.

The significant result of these beam distortion studies was the absence of noticeable spatial or temporal distortion of the attenuated beam at 0.7 MW/cm^2, even though this laser intensity (on Fig. 3, for 0.5 Torr SF_6) exceeded the intensity for the onset of saturation. This indicates that the intensity for the onset of saturation is a conservative estimate of the safe limit for saturation-free operation of the gas attenuator. The oblique line in Fig. 3 may therefore be extended to somewhat higher laser intensities without compromising the distortion-free operation of the gas attenuator. Additionally, an observation of the absorption characteristics (i.e., attenuation in dB versus laser intensity) is proven to be a more sensitive probe of saturation than spatial or temporal beam distortion studies.

D. Pressure dependence of the absorption characteristics

The total pressure of the gases in the attenuator may be used as a further parameter to affect the saturation intensity and thereby extend the available effective intensity range of the attenuator for distortion-free attenuation. At a given attenuation (determined by the partial pressure of SF_6), the total pressure may be altered by changing the partial pressure of the buffer gas.

Experiments were performed to study the pressure dependence of the saturation intensity. In each case, the partial pressure of SF_6 was fixed at 1.0 Torr while varying the

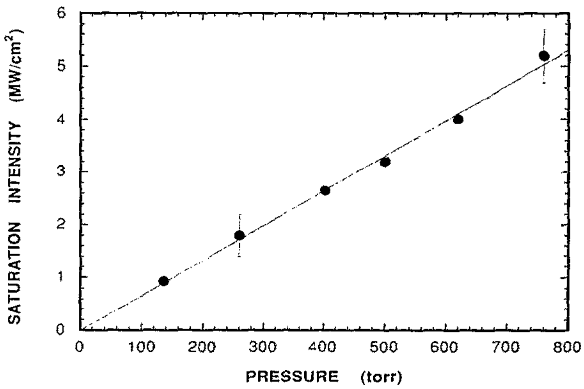

FIG. 6. Absorption saturation intensity as a function of total pressure in an SF_6/He attenuator. The partial pressure of SF_6 was 1.0 Torr for all the data points. The solid line indicates a linear fit to the experimental data.

background pressure. The saturation intensity (I_s) is shown as a function of total gas pressure in Fig. 6. A linear increase in I_s with increasing pressure is observed. The rate of increase, based on a linear regression fit, is estimated to be ~ 5.2 MW/cm^2 per atm. As expected, the linear fit passes through the origin.

Equation (8) suggests a P^2 dependence for the variation of I_s with total pressure. However, our experimental results indicate a linear variation of I_s with pressure. Previous experiments conducted on the absorption of laser radiation by polyatomic molecules (with a relatively high density of states) under collisional and collisionless conditions have revealed the relative constancy of $\Delta\nu$ with pressure in the collisional regime.[8–10] This has been shown to follow from a multitier classification of energy levels in the quasicontinuum of such molecules, rather than the simple two-level approach presented in Eq. (8).[10] The lack of pressure dependence of $\Delta\nu$ (for absorption in the collisional regime) results in a saturation intensity proportional to τ^{-1} and hence to the total pressure, consistent with the experimental results presented in Fig. 6.

Based on the observed trend, it is expected that elevating the total pressure in the gas attenuator to 2 atm will increase the saturation intensity to ~ 10.4 MW/cm^2. Further increase in I_s, if desired, should be possible with multiatmospheric attenuation modules.

V. CONCLUSION

We have presented, in this article, the basic principles and detailed operational characteristics of a novel technique for the attenuation of high-power TEA CO_2 laser pulses using a binary SF_6/He gas attenuator. The saturation intensity for the attenuator at a total pressure of 1 atm was ~ 5.5 MW/cm^2, which represents an improvement of approximately three orders of magnitude over conventional single component gas attenuators of comparable dynamic range.

Linear tunability of the attenuator in the 0–31-dB range (for a 10-cm gas cell length) was obtained simply by adjusting the partial pressure of the absorber (SF_6). The possibility of further attenuation (~ 60 dB) was demonstrated and calibration curves were obtained for our experimental cell. Further increase in SF_6 partial pressure should allow >60 dB attenuation. The effect of buffer gas pressure was carefully measured and the results indicate that further augmentation of the saturation intensity, beyond 5.5 MW/cm^2, is feasible using multiatmospheric attenuator modules. Detailed beam distortion studies indicate that the attenuator introduces no spatial, temporal, or phase distortion (leading to frequency change or beam divergence) in the unsaturated regime.

In addition to simplicity of operation, the SF_6/He binary gas attenuator has the advantages of being nonflammable, noncorrosive, and nontoxic. These qualities are operationally desirable in the attenuation of high-power CO_2 laser pulses where the attenuator will absorb a significant amount of laser energy.

Although the experiments discussed in this article were conducted using 10.59 μm pulsed TEA CO_2 laser radiation, the basic principle of binary gas attenuation is applicable across the frequency spectrum, with the choice of a suitable absorber depending on the laser frequency. The inherent scalability of this technique should make it ideal for the continuously variable, distortion-free attenuation of any high-power laser system.

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