All-optical power limiting of CO_2 laser pulses using cascaded optical bistable elements

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We report the first all-optical power limiter based on cascaded InSb étalons. The power limiting effect is due to a dispersive nonlinearity in InSb at room temperature as a result of generation of free carriers through two-photon absorption of 10 μm radiation. The efficiency and dynamic range of this all-optical circuit are discussed.

The development of optically bistable and other related devices has been rapid with many recent publications concentrating on their application as all-optical circuit elements.[1–5] This letter reports the first realization of an optical power limiting circuit using two optically bistable elements–étalons fabricated from a nonlinear dispersive material which consequently exhibit power-dependent transmission characteristics.

In this work we define an optical power limiter to be a device which for all power levels above a well-defined minimum (and below some maximum value) transmits a constant level of optical power. The possible applications of such an all-optical circuit are considerable. For example, it may serve as an essential unit in optical computation as a stabilizer of bias levels or it may be used in pulsed laser systems to ensure reproducible peak laser power or to control pulse shapes.

The limiting optical circuit presented here is based on two elements of InSb in a simple cascaded configuration. Optical bistability in InSb étalons due to the generation of free carriers through two-photon absorption has been described previously.[6] More recently we have reported quasi-steady-state optical bistability on several Fabry–Perot orders.[7] These devices operate at room temperature and exhibit a relatively low insertion loss in the important wavelength region around 10 μm.

The circuit studied consisted of two plane-parallel intrinsic-InSb étalons (carrier concentration $\sim 1.7\times 10^{16}$ cm^{-3}) of thickness 120 and 230 μm, respectively. The detailed theoretical background and switching characteristics are discussed by Ji *et al.*[7] where a single element is considered. The power limiting region of the input/output characteristic of a single nonlinear InSb étalon has been improved upon by using two cascaded elements.

The experimental layout and optical circuit is shown schematically in Fig. 1, the details of which are partly described elsewhere.[7] The output from a hybrid transversely excited atmospheric CO_2 laser operating on a single line at a wavelength 10.6 μm and with a pulse length (FWHM) of 1–1.5 μs was focused down to a spot size of 1 mm diameter on the first étalon. A lens between the two étalons imaged the output from the back plane of the first étalon to the front plane of the second. The input, output, and intermediate pulses were detected by three Labimex CdHgTe room-temperature detectors (response time $\sim$ 1 ns) and viewed either on a Tektronix 7104 oscilloscope (bandwidth 1 GHz) or a Tektronix 7844 dual beam oscilloscope (bandwidth 400 MHz) with a Thomson–CSF dual trace digitizer. The digitized traces were processed and stored by an HP85 microcomputer interfaced directly to the digitizer. 200 μm pin holes were mounted in front of the detectors restricting the detection of the transmitted pulses to the central uniform portion of the illuminating beam, in order to approximate plane wave uniform irradiation.

To avoid desynchronism between the detectors, which could generate false hysteresis loops even without a sample, the time delays on the oscilloscope were adjusted to obtain a straight line in the x-y plots of input and output signals, when using both pairs of detectors in the absence of a sample. Detector 2 was then adjusted without the second element but with the first element in position so as to detect the same pulse shape as detector 3. This ensured that detector 2 was indeed monitoring the signal focused onto the second étalon. Attenuators were placed in the incident beam to permit examination of the performance of the circuit throughout the dynamic range of input irradiance.

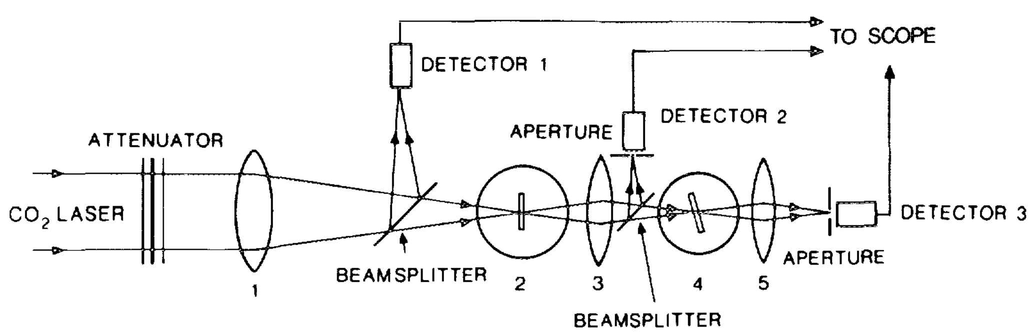

FIG. 1. Experimental arrangement. (1) Focusing lens, (2) first InSb étalon, (3) imaging/focusing lens, (4) second InSb étalon, (5) imaging lens.

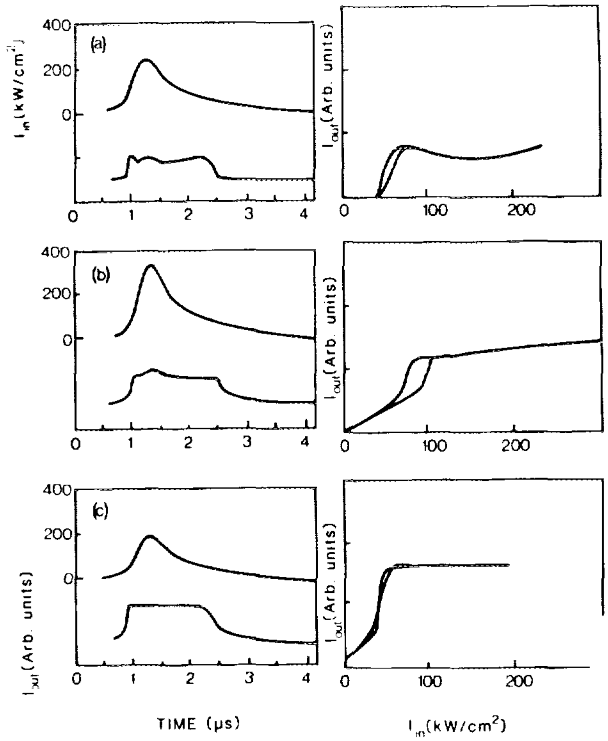

FIG. 2. Input/output pulse shapes and irradiance characteristics. Left: irradiance vs time for input (upper) and output (lower) pulses. Right: Input/output irradiance characteristics. (a) First element only; (b) second element only.

Assuming low absorption, the radiation induced phase shift in a nonlinear étalon is directly proportional to its thickness. Thus the thinner the sample the higher is the incident irradiance required to achieve the same phase shift. As the thinner étalon also has a somewhat higher transmission it was consequently chosen to be the first of the two cascaded elements. (Optimization of the individual and relative étalon thicknesses was not attempted.) Limiter operation was obtained by operating both elements at irradiance levels above that required to switch to their on-resonant state (determined by the choice of initial detuning). Thus increasing irradiance tuned them from their high transmission state towards one of lower transmission, hence maintaining a

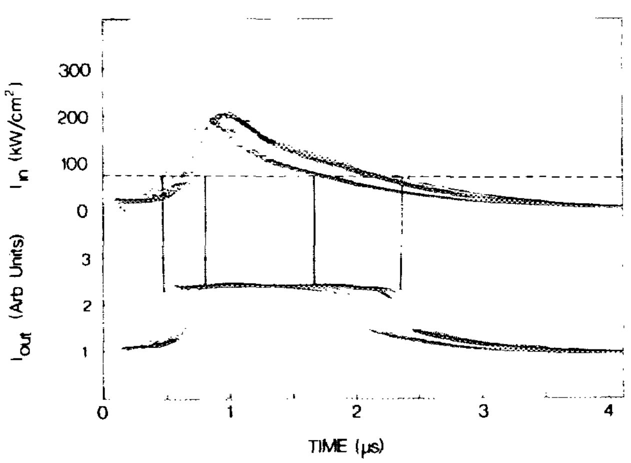

FIG. 3. Overlay of 25 consecutive input pulses (top) plus the resultant transmitted pulses (bottom), for the complete dual element limiter.

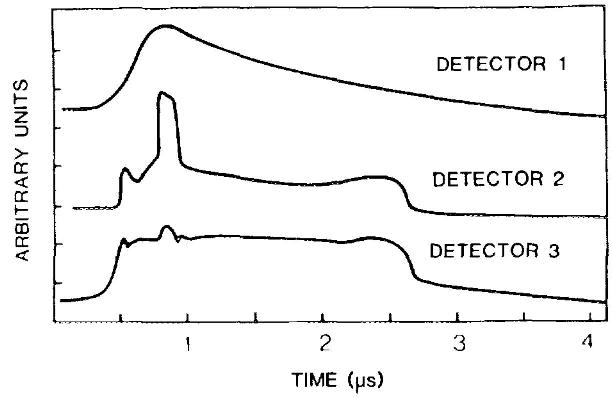

FIG. 4. Input pulse (top), pulse after first element (middle), and output pulse from second element (bottom). Showing the effect of a high peak input power sufficient to induce switching of the first element.

nearly constant output. The result is shown in Fig. 2, which shows input/output pulses and irradiance characteristics for each element individually and the combination.

A figure of merit can be defined for the limiter as the ratio between the fractional change of the output and input irradiances, given by

$$\Delta = \frac{\Delta I_{out}/I_{out}}{\Delta I_{in}/I_{in}} = \frac{\Delta I_{out}}{\Delta I_{in}}\frac{I_{in}}{I_{out}}.$$

Thus $\Delta = S/T$, where T is the transmission and S corresponds to the slope in an x-y plot of instantaneous incident and transmitted irradiance. Thus, to improve the performance of the power limiter Δ has to be decreased. This can be achieved by either decreasing S and/or increasing transmission.

For this two-element system we can express Δ as

$$\Delta = \Delta_1\Delta_2,$$

where

$$\Delta_1 = S_1/T_1, \quad \Delta_2 = S_2/T_2.$$

It is clear from Fig. 2 that both (S_1/T_1) and (S_2/T_2) are smaller than unity and hence a low value of Δ can be achieved by combining the two elements.

The excellent performance of the power limiter/stabilizer can be seen from the experimental results shown in Fig. 3, where 25 input traces and the corresponding transmitted pulses have been plotted. The variation in the input irradiance is provided by both the pulsed nature of the radiation and instabilities induced in the laser. The critical irradiance above which strong limiting action occurs can be clearly identified. Any increase in input irradiance over ~70 kW/cm^2 does not add to the transmitted irradiance up to at least an irradiance of 220 kW/cm^2. This increase of 210% can be compared with less than 7% change in the output and consequently the figure of merit, Δ, has a value less than 0.033.

Another important parameter is the dynamic range of the device. There exist both an upper and a lower limit to the operating range. The lower is determined by the irradiance required to switch the individual elements to their on resonance, high transmission, states. The upper limit is reached when the input irradiance is sufficient to tune the first element onto the next Fabry–Perot resonance. The operating regime for this two-element device is 70–400 kW/cm^2.

The upper limit can be extended if a slightly poorer performance is acceptable because, as shown in Fig. 4, the second element continues to provide limiting action even after the first element switches to higher transmission. The consequence of this switch occurring is a 25% change in final output. However, further increases in input continued to be limited, at this new level, up to at least 1 MW/cm^2, thus maintaining a low overall Δ value while increasing the dynamic range to over 14.

A further significant parameter is the insertion loss of both the nonlinear elements and the associated optics. In these experiments the latter was measured to be $\sim$45% but clearly could be improved by coated optics and removal of the monitor beamsplitters. Each limiter element typically transmits 50%–60% when on resonance. Thus at the input irradiance level at which the limiting action comes into effect the total system transmission is $\sim$15%. By minimizing the losses from optical components and reducing background free-carrier absorption this transmission could be increased to over 50%.

In conclusion, we have demonstrated that, by cascading two elements of InSb, a high performance limiter can be constructed for CO_2 laser radiation. This will find immediate application in optical logic circuits, and in controlling laser pulses. The dynamic range and efficiency of this optical circuit can be improved by optimizing the various parameters such as étalon thickness, reflectivities, initial detuning, etc., the details of which will be reported at a later date. The concept of staging limiter action to improve performance and extend the dynamic range should be generally applicable to all limiters of this type and should be ultimately implemented in the form of integrated multicavity devices.

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