Low-voltage device for passive mode locking of pulsed infrared lasers

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A reliable mode-locking device which can be used to generate short CO_2 laser pulses has been developed and investigated. The device uses p-type germanium filters cooled to 78 °K, having a low threshold (10–15 MW/cm^3) and a short bleaching time (≤ 0.1 nsec). As a whole, the system can withstand more than 10^5 lasing cycles without appreciable damage to the antireflection coatings and laser elements.

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In the infrared range, mode locking has only been achieved for a CO_2 laser. Gas filters using heated carbon dioxide[2] and SF_6 with added He (Ref. 3), and also uncooled semiconducting filters comprising room-temperature p-type germanium[4,5] have been used as nonlinear absorbers. Disadvantages of gas filters are their slow response (~2 nsec) (Ref. 2) and the resonant character of the absorption. In particular, SF_6 can only be used for lasing on the $P(20)$ line of a CO_2 laser (Ref. 3).[1)] Compared with other nonlinear filters, p-type germanium semiconducting filters have many important advantages including their short relaxation time (~1 psec) and their broad infrared absorption spectrum. In order to avoid high reflection losses, antireflection coatings were applied to the faces of these filters. It was shown experimentally that successful operation of germanium filters at $T = 300$ °K requires high optical intensities (10–40 MW/cm^2) (Ref. 4) close to the damage threshold of the filter coatings and the laser optical elements. This has the result that systems using p-Ge filters have poor reliability and a short life at $T = 300$ °K. For example, it was reported in Ref. 5 that a nonlinear p-Ge filter could withstand between 10 and 30 lasing cycles at $T = 300$ °K. As a result of these disadvantages, neither gas nor semiconducting filters have been widely used up till now.

We proposed a method of mode locking in infrared lasers[5] in which the bleaching threshold of a p-type germanium semiconducting nonlinear filter could be reduced by more than an order of magnitude by decreasing the temperature and selecting an appropriate carrier density. A decrease in the bleaching threshold should clearly substantially increase the reliability and life of the total laser system.

It was shown in Ref. 7 that the dependence of the absorption coefficient α on the optical intensity I in p-type germanium with a free carrier density of 10^{12} – $3 \cdot 10^{15}$ cm^{-3} at $T = 78$ °K takes the form

$$\alpha(I) = \frac{\alpha_0}{1 + I/I_s}, \quad (1)$$

where α_0 is the absorption coefficient at low optical

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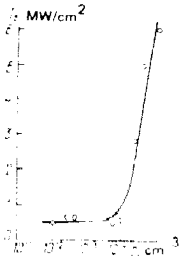

FIG. 1. Experimental dependence of the saturation parameter I_S on the hole density p in germanium at T=78°K.

intensities; I_s is the saturation parameter, for which the dependence on the free carrier density is plotted in Fig. 1. At T=78°K the value of the bleaching parameter is more than an order of magnitude lower than that at T=300°K and depends strongly on the free carrier density. The decrease in the parameter I_s and its density dependence occur because at T=78°K the relaxation process of the equilibrium population is governed by interelectron collisions and emission of acoustic phonons rather than by a relaxation process involving optical phonons, as is found at T=300°K.

The present paper describes and reports an investigation of a low-voltage device developed for mode locking of a CO_2 laser (Fig. 2).

The device consists of a cryostat containing a p-type germanium nonlinear filter.[1] The filter holder is cooled by liquid nitrogen which determines the temperature of the filter. The cryostat windows are made of NaCl plates mounted at the Brewster angle. The low-vacuum chamber of the cryostat is evacuated to a pressure of 1 Pa after which the device is disconnected from the vacuum pump and placed in the laser resonator.

Cylindrical filters of 27 mm diameter having the parameters given in Table I were used. When using filters of this thickness, it is necessary to allow for interference effects which result in modulation of the

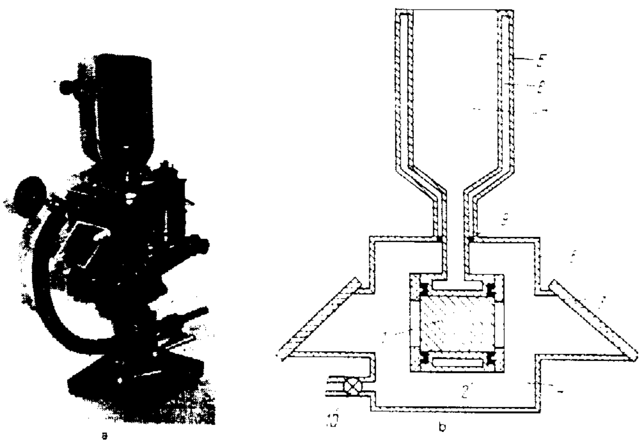

FIG. 2. External view (a) and schematic diagram of mode-locking device (b): 1) nonlinear filter; 2) indium heat seal; 3) NaCl window; 4) low-vacuum container; 6) high-vacuum container; 7) container for pouring in liquid nitrogen; 8) low-vacuum chamber; 9) seal between low-vacuum and high-vacuum chambers; 10) vacuum pumping valve.

TABLE I.

Sample No.	p, cm^{-3}	I_s, MW/cm^2	d, cm	α, cm^{-1}	αd
1	$1 \cdot 10^{14}$	1	3.7	0.036	0.13
2	$1.5 \cdot 10^{14}$	1.4	3.7	0.055	0.2
3	$2 \cdot 10^{14}$	2	3.7	0.075	0.26
4	$3 \cdot 10^{14}$	2.7	3.7	0.105	0.39
5	$6 \cdot 10^{14}$	5.2	1.0	0.29	0.29
6	$1.2 \cdot 10^{15}$	7	1.0	0.42	0.42

transmission as a function of the wavelength with the period $\Delta\lambda = \lambda^2/2nd$ which n is the refractive index; d is the thickness of the filter. The transmission varies between $[(1-R)/(1+R)]^2$ and 1 (R is the reflection coefficient of a single face). In order to minimize reflection losses, antireflection coatings were applied to the faces of the filter, comprising a combination of ZnS–Ge layers deposited under high vacuum conditions using an ionic thermal deposition technique.[9] In this case, the reflection coefficient of a single face was less than 2%. The coatings could withstand repeated cooling to T=78°K at a rate of 20°K/min. The optical strength of the coatings for CO_2 laser pulses of 100 nsec duration was ~15 MW/cm^2.

Mode locking with the aid of this device was investigated using a transverse-discharge CO_2 laser with ultraviolet preionization. The active region was 400 mm long, the discharge cross section was 10×20 mm, and the energy input to the laser was 100 J/liter. The following mixtures were used: 20% CO_2–5% N_2–75% He(I) and 40% CO_2–10% N_2–50% He(II). The total gas pressure was controlled and maintained at around 1 atm. A laser resonator of length L_0 was formed by a gold-coated spherical copper mirror having a radius of curvature R_0=2.5 m and by a pure germanium plane semitransmitting mirror 4 mm thick. The highest reflection coefficient of the exit mirror allowing for interference effects was 78%. This resonator was equivalent to a confocal one of length

$$L_{eq} = 2\sqrt{L_0(R_0 - L_0)}. \qquad (2)$$

The mode-locking device was inserted in the resonator near the plane exit mirror. In this case, the ratio of the radiation intensities at the filter and in the active medium is given by

$$m_0^2 = [r(L_f)/r(0)]^2 = 1 + (2L_0/L_{eq})^2, \qquad (3)$$

where $r(0)$ and $r(L_f)$ are the spot radii at the filter and in the active medium, respectively, provided that lasing

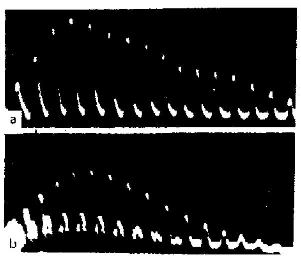

FIG. 3. Trains of CO_2 laser pulses: a) mixture I, sample No. 2, L_0 = 1.4 m; b) mixture II, sample No. 3, L_0 = 1.55 m.

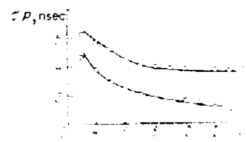

FIG. 4. Pulse shortening along the train for $L_0 = 1.45$ m: 1) mixture I, sample No. 2; 2) mixture II, sample No. 3.

takes place in the TEM_{00} mode. Thus, by altering L_0, it is possible to vary the intensity of the initial fluctuations at the filter, which is important for optimizing the operation of the nonlinear filter.

The pulse train generated by the laser was recorded using an FPU-500 photon drag detector[5] and an S7-10B oscilloscope. The resolution of the recording system was 1 nsec.

Stable mode locking could be achieved using this device. Typical pulse trains are shown in Fig. 3. Clear mode locking and a pulse train with a high contrast D [Fig. 3(a)] are only found under certain conditions. In other cases, additional pulses are observed per axial period [Fig. 3(b)]. This occurs when the nonlinear filter is capable of bleaching a large number of fluctuations rather than just one. As the train develops, shortening of individual pulses is observed (Fig. 4). This is in good agreement with qualitative reasoning on the successive passage of a short radiation pulse through nonlinear amplifying and absorbing media.[1]

In order to determine the conditions for obtaining a train with the maximum contrast, an investigation was made of the influence of the resonator length, i.e., of the value m_0^2, and the gas mixture composition, and the degree of doping of the filter material. Corresponding dependences for various filters and gas mixture compositions are plotted in Fig. 5. This gives the dependences of the total contrast D_0, which is the ratio of the amplitude of the principal pulse in the train to the amplitude of the second pulse formed in the same period, and also gives the ratio of the intensity of the principal pulse to the background radiation intensity between pulses D_f, as a function of the resonator length L_0. When L_0 is small, i.e., when the intensity at the filter is much lower than I_s, the filter losses are high for most of the fluctuations, so that only the few large fluctuations are substantially amplified in the laser. Thus, the small fluctuations are efficiently suppressed and a train with a high contrast is formed. As L_0 increases, the optical intensity increases and an increasingly large number of fluctuations can be supported near the lasing threshold. The contrast decreases until the second largest fluctuation becomes sufficient to bleach the filter. This fluctuation is then isolated in the individual pulse and the contrast D_f increases rapidly whilst D_0 continues to decrease. This reasoning explains the dependence of the contrast D_f on L_0 for filters having densities $p \approx 1.5 \cdot 10^{14}$ [curve 3 in Fig. 5(a)] and $2 \cdot 10^{14}$ cm^{-3} (curve 4). It can be seen from the figure that the position of the maximum of D_f^{-1} differs for the two samples, the maximum of D_f^{-1} for the filter with the lower carrier density and lower I_s being shifted toward shorter resonator lengths and weaker focusing m_0^2. It can be seen from Eq. (3) that the values of L_0 corresponding to the maximum of curve 3 in Fig. 5(a) correspond to an optical intensity at the filter 1.5 times higher than that for curve 4. This was to be expected since the bleaching parameter for the filter corresponding to curve 4 is 1.5 times smaller.

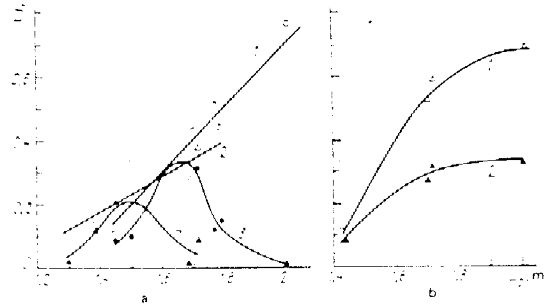

FIG. 5. Dependences of the contrast on the resonator length: a) mixture II; 1) sample No. 3, D_0^{-1}; 2) sample No. 2, D_0^{-1}; 3) sample No. 3, D_f^{-1}; 4) sample No. 2, D_f^{-1}; b) mixture I, sample No. 2; 1) D_0^{-1}; 2) D_f^{-1}.

An important parameter was the radiation power in the individual spikes. In the experiments described above the power in the maximum-amplitude spike reached 200 kW. In this case, the diameter of the spot at the filter was ~4 mm, which corresponded to an optical density of ~5 MW/cm^2 at the filter. In our case, the optical diameter of the filter is 25 mm. Thus, by using a suitable cell containing the active medium, the diameter of the spot at the filter could be increased sixfold so that a considerably higher power could be obtained in the spikes without appreciable deterioration in the operation of the nonlinear filter.

Experiments carried out using different filters showed that, under our conditions, the optimal filters from the point of view of contrast, operating stability, and feasibility of using available antireflection coatings are those having a hole density $p = (1.5-2.0) \cdot 10^{14}$ cm^{-3} and $\alpha d = 0.2-0.26$ for resonator lengths of ~1.45 m, which corresponds to $m_0^2 \sim 2$. It has been noted that the optical intensity at the filter is 5 MW/cm^3. This is appreciably lower than the damage threshold of the antireflection coatings, which is 15 MW/cm^2 for pulses of 0.1 μsec duration.

Operating experience showed that this device could withstand more than 10^5 shots without appreciable damage to the antireflection coatings and the nonlinear filter material. Since the bleaching threshold was low, this filter could be used for stable mode locking with a high contrast in the train and a long service life.

[1)] In the opinion of the reference, SF_6 can be used not only for lasing on the $P(20)$ line of a CO_2 laser but also for other lines because SF_6 has an absorption band coinciding with the P branch of the CO_2 vibrational–rotational band.

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