Passive mode locking and Q switching of an erbium 3 μm laser using thin InAs epilayers grown by molecular beam epitaxy

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Passive mode locking and Q switching has been achieved for the first time in an Er^{3+}:YSGG laser at $\lambda = 2.8$ μm using ultrathin single-crystal InAs epilayers grown on GaAs substrate which were subsequently bombarded with 15 keV protons at a dose of 10^{13} cm^{-2}. The bleaching effect was due to a dynamic Moss–Burstein mechanism with a fast (< 100 ps) recovery time. In the case of passive mode locking, pulses of 10 MW power were generated at $\lambda = 2.8$ μm.

In the last 15 years a new type of 3 μm band laser, based on erbium-doped crystals (Er^{3+}:YAG, Er^{3+}:YSGG, etc.) has been developed. These lasers operate at high efficiency at room temperature using flashlamp pumping in the free-running, Q-switching, and active mode-locking modes.[1,2] Recently a continuous-wave generation of these type of lasers using krypton ion laser pumping was reported.[3] 3 μm band erbium lasers are successfully used in laser surgery,[4,5] nonlinear optics,[6] and laser spectroscopy,[7] and are extremely promising in optical telecommunications using fluoride optical fibers.[8]

To date electro-optical methods have mainly been used for Q switching and mode locking these types of lasers, because at present bleachable passive shutters based on solution of organic dyes or color center crystals (as used in visible and near-infrared lasers) do not exist for the 3-μm band. An appropriate passive Q-switching material would make it possible to create a simple 3-μm high-repetition-rate giant pulse laser for medical applications. Alternatively, a passive shutter with a small enough absorption recovery time could produce passive mode locking of erbium lasers giving pulse durations down to 3 ps, corresponding to the inverse width of the erbium laser's gain profile (9–12 cm^{-1}).

Semiconductor thin films are known to exhibit a wide range of nonlinear effects, and these have been successfully used to mode lock near-infrared GaAs diode (0.85 μm)[9] and NaCl color center (1.6–1.7 μm)[10] lasers. Recently passive mode locking of KCl:Li and RbCl:Li mid-infrared color center lasers ($\lambda = 2.7$–2.8 μm) using HgCdTe multiple-quantum-well semiconductor structures has also been reported.[11]

At room temperature the optical band edge of InAs (0.35 eV) corresponds to a wavelength of 3.54 μm, and this narrow band gap results in a low electron effective mass. The small effective mass produces large dynamic Moss–Burstein shifts in the absorption edge at moderate carrier densities and an electron concentration of 5×10^{17} cm^{-3} is sufficient to shift the bend edge to 0.44 eV, corresponding to $\lambda = 2.8$ μm laser photon energy.

Recent advances in the molecular beam epitaxial (MBE) growth technology[12,13] of InAs have now yielded high-quality single-crystal epilayers on GaAs substrates. Initial saturable absorption measurements performed with 3.3-μm-thick InAs epilayers using 3 μm radiation from an actively mode-locked erbium laser showed a very strong bleaching effect at moderate energy fluences, occurring due to the dynamical Moss–Burstein shift with fast absorption recovery times.[14]

Improved picosecond pump-probe experiments performed with 0.27-μm-thick epilayers near the absorption edge ($h\nu = 0.35$–0.5 eV) using 10–15-ps duration $\mathrm{LiNbO_3}$ parametric generator pulses[15] showed a large absorption decrease at the excitation frequency. Recovery times of 100–200 ps measured in the as-grown samples dropped to 60–100 ps after proton bombardment at a proton energy of 15 keV and a dose of 10^{13} cm^{-2} (Fig. 1). Even in the former case the measured absorption recovery time was several orders of magnitude smaller than could be explained by a radiative recombination mechanism alone. We believe that the absorption recovery is dominated by nonradiative photoexcited carrier recombination at the interface between the GaAs substrate and the InAs epilayer. In the case of proton-bombarded samples the carrier recombination rate is further increased due to creation of additional volume defects in the InAs.

The InAs absorption saturation stars at excitation beam fluences of a few μJ/cm^2,[14] in good agreement with the band-filling model.

For passive mode locking the $\lambda = 2.8$ μm erbium laser we used a 0.27-μm-thick InAs epilayer grown by MBE on a 0.25-mm-thick (001) Cr-doped semi-insulating GaAs substrate whose sides were parallel to $\cong 0.2°$. The epilayer

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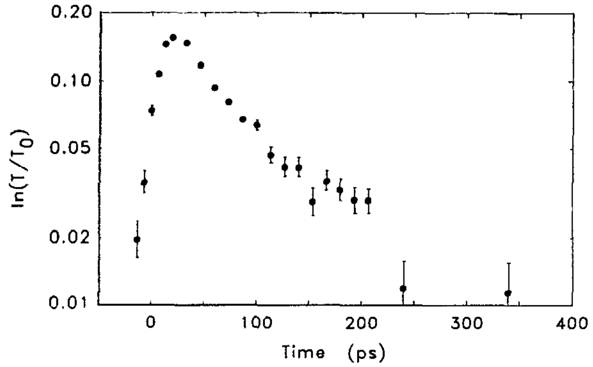

FIG. 1. Time resolved pump-probe experiment curve for 0.27-μm proton-bombarded (10^{13} cm^{-2} dose) InAs sample. Pump and probe frequencies are 3800 cm^{-1}, T/T_0: relative transmission change.

was subsequently bombarded with 15-keV protons at a dose of 10^{13} ions/cm^2. The plate was put at an angle of incidence of 60° in the laser resonator (Fig. 2) in order to decrease Fresnel losses, to eliminate etalon effects and to avoid optical damage of the InAs layer by increasing the laser spot area on the sample surface. The small signal absorption at $\lambda = 2.8$ μm of the 0.27-μm InAs epilayer was 15%

The active element in the laser was an Er^{3+}, Cr^{3+}-doped YSGG crystal[2] in the form of a rod ∅5×73.5 mm with Brewster-angled ends (Cr^{3+} ions act here as an efficient sensitizer for the laser ions Er^{3+}). It was pumped by a Xe flashlamp with a typical pump energy of 100 J and a repetition rate of 1 Hz. The laser resonator was formed by two concave dielectric mirrors (M_1, M_2) with a 2.5-m radius of curvature and reflection coefficients of 70% and 100%. The optical length of the resonator was 75 cm, corresponding to a round-trip time of 5 ns.

The output radiation of the laser was recorded with a fast Ge photodiode (PD) (Fig. 3) and was in the form of a train of about 20 pulses with a total energy of 5–10 mJ, the spatial mode being TEM_{00} and beam diameter 1 mm. The estimated pulse duration was 20–30 ps, taking into account the passive shutter recovery time and the active element gain bandwidth of 12 cm^{-1}.

There is also the possibility that the band-filling effect (with a typical recovery time of ~100 ps) may have an initial very fast component due to the optical generation of a nonthermalized carrier distribution. Before they thermalize in the conduction band, hot carriers can manifest themselves in an ultrafast saturation effect with a characteristic recovery time of the order of the electron thermalization time, typically ~200 fs (using data obtained for GaAs).[16] The intracavity intensity in the laser reaches 10^9 W/cm^2, exceeding the estimated intensity of ~10^7 W/cm^2 required for the generation of a nonthermal carrier distribution. This estimate derives from the assuming that the rate of nonequilibrium carrier excitation due to light absorption and the rate of carrier thermalization are of the same order. We conclude that hot-carrier effects in InAs may be playing an additional role during the formation of the laser pulses.

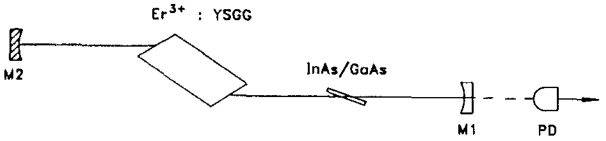

FIG. 2. Setup for mode-locking experiment.

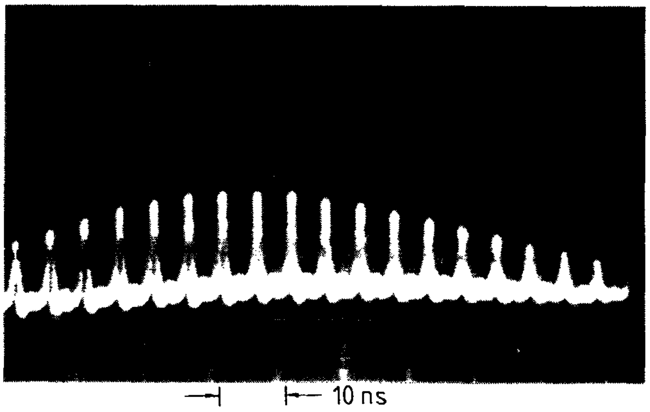

FIG. 3. Output of a passively mode-locked Er^{3+}:YSGG laser ($\lambda = 2.8$ μm).

It should also be noted that as well the mode-locking effect, the epilayer simultaneously produces Q switching of the resonator. By using plane-parallel spectral selectors within the resonator, a smooth giant output pulse of 100 ns duration can easily be produced. The same effect can be achieved by placing the InGaAs/GaAs absorber at normal incidence to the beam and adjusting it to be parallel with one of the laser mirrors. Due to the high refraction index $n=3.5$ and correspondingly large Fresnel reflection from the semiconductor, a spectral selection effect occurs that is sufficient to narrow the spectrum to few longitudinal modes, producing smooth output pulses.

In conclusion, for the first time passive mode locking and Q switching has been achieved in a $\lambda = 2.8$-μm erbium laser with the use of ultrathin single-crystal InAs epilayers grown by MBE on GaAs substrates. This provides the possibility, for the first time, of creating a passively Q-controlled all solid-state room-temperature laser source with intense pulses for the 3-μm region.

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