Far-IR heterojunction lasers tunable to 46.2 μm

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The spectral range of diode lasers has been extended substantially further into the far-IR region. Long-wavelength lasing has been achieved at 46.2 μm in heterojunction lasers using quaternary PbSnTeSe solid solutions. The longest wavelength achieved previously was 34 μm.

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Attempts to extend the spectral range of semiconductor lasers into the far-IR region run into several fundamental difficulties.[1] The difficulties stem primarily from plasma effects which occur in the semiconductors and cause a strong attenuation of electromagnetic waves at frequencies below the plasma frequency. The largest wavelength at which lasing has been achieved previously in semiconductor lasers is 34 μm (Ref. 2).

In the present experiments we have achieved lasing at 46.2 μm in heterojunction lasers using quaternary PbSnTeSe solid solutions. The possibility of using the PbSnTeSe system was first pointed out by Davarashvili *et al.*[3]; lasing was first achieved in this system by Starik *et al.*[4]

The $(PbSe)_{0.80}(SnTe)_{0.20}$ single crystals were grown from the vapor phase and had an initial hole concentration $\sim 10^{19}$ cm^{-3}. A subsequent annealing in metal vapor inverted the conductivity type and reduced the carrier concentration to 10^{17}–10^{18} cm^{-3}. Laser heterostructures were fabricated by photostimulated gas-phase epitaxy. A wide-gap *p*-type epitaxial layer was deposited through the use of $PbTe_{0.68}Se_{0.32}$.

Electrodes were attached to the *p*-type and *n*-type regions of the heterostructures through chemical deposition of gold. The resonators were fabricated by cleaving the crystals along (100) planes. The laser diodes were soldered to a heat sink with an In–Ag–Au alloy. The resonators were typically 300–500 μm in size.

A Perkin-Elmer monochromator with a grating with 28.8 lines/mm was used to study the output spectrum. The light was detected with a Ge ⟨Be⟩ photodetector on the cold stage of a nitrogen-free helium cryostat with a cesium iodide entrance window. The entrance aperture of the detector was reduced to 1.5° to suppress background illumination. Spherical mirrors were used to focus the output from the lasers onto the entrance slit of the monochromator and the photodetector.

The laser diodes were studied during pulsed pumping. The pulse length was 4 μs, and the repetition frequency was 100 Hz. The lasers could be tuned over a broad wavelength interval by changing their temperature. Specifically, the output wavelength varied by a factor of nearly two from 46.2 μm at $T = 6$ K to 24.3 μm at $T = 78$ K (Fig. 1). This large change resulted from the large relative change in the gap width.

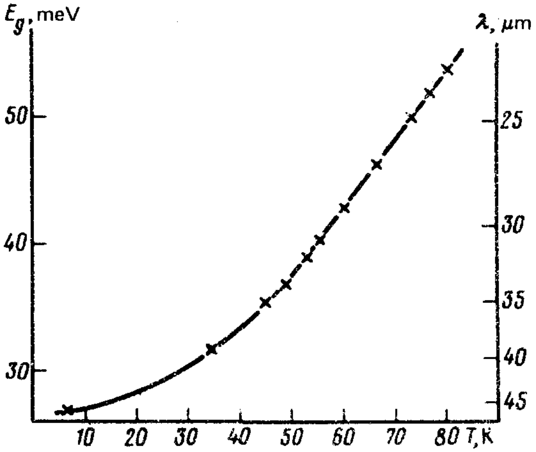

FIG. 1. Temperature-induced change in the output wavelength of a $(PbSe)_{0.80}(SnTe)_{0.20}$–$PbTe_{0.68}Se_{0.32}$ laser diode.

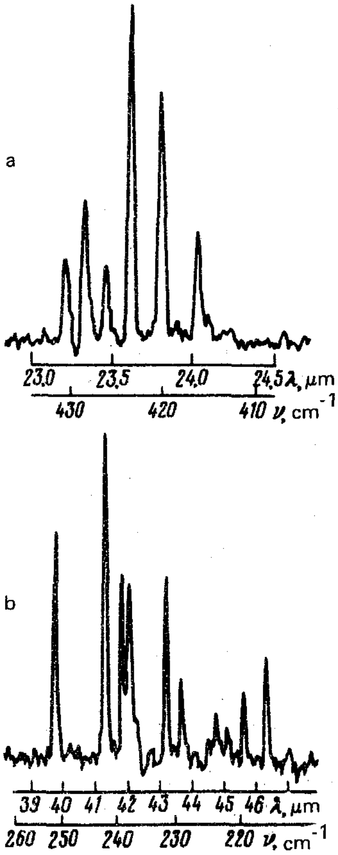

FIG. 2. Output spectra of a $(PbSe)_{0.80}(SnTe)_{0.20}$–$PbTe_{0.68}Se_{0.32}$ laser diode. a—78 K; b—6 K.

Figure 2 shows the output spectra of a $(PbSe)_{0.80}(SnTe)_{0.20}$–$PbTe_{0.68}Se_{0.32}$ laser diode at liquid-nitrogen and liquid-helium temperatures. At liquid-nitrogen temperature the spectrum was recorded at a current 1.5 times the threshold. The width of this spectrum is $\sim 15\ \text{cm}^{-1}$. A mode structure can be seen clearly in the spectrum. At liquid-helium temperature the spectrum was recorded at a current five times the threshold. The spectral width was greater, $30\ \text{cm}^{-1}$. The output spectrum is greatly distorted near 40 μm by absorption due to rotational transitions of water vapor in the atmosphere (the optical pathlength in the atmosphere during the measurement of the spectra exceeded 2 m).

The threshold current density decreases comparatively little (by a factor of only three) in these diodes as the temperature is lowered from 78 to 6 K. At 78 K the threshold current density is 9.5 kA/cm^2. The output spectra at liquid-helium temperatures initially exhibit the short-wavelength modes (42 μm); the long-wavelength modes (up to 46.2 μm) appear only when the current is well above the threshold. The intensities of these long-wavelength modes are lower than those of the short-wavelength modes. These experimental results may mean that as the temperature is lowered, and the wavelength correspondingly increased, there is a substantial increase in the optical loss because the plasma region is being approached. Estimates show that near the plasma boundary the optical loss is several hundred reciprocal centimeters and increases sharply (by a factor of more than 1.5) over a narrow spectral interval ~ 10 cm^{-1}. This effect is responsible for the much higher threshold for the excitation of the long-wavelength modes; as a result, the long-wavelength boundary of the tuning range may be moved back slightly because of a temperature-induced change in the gap width.

We believe that this is far from being the maximum wavelength obtainable from lead–tin chalcogenide laser diodes. As the carrier concentration is lowered, the plasma frequency can be reduced, so that the transparency boundary of the semiconductor can be moved in the long-wavelength direction, to the residual-ray band. In addition, the imposition of magnetic field may make it possible to produce transparency windows for far-IR electromagnetic radiation in the semiconductor plasma.

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