STIMULATED EMISSION IN FAR-IR WAVELENGHT RANGE FROM HGCDTE QUANTUM WELL STRUCTURES

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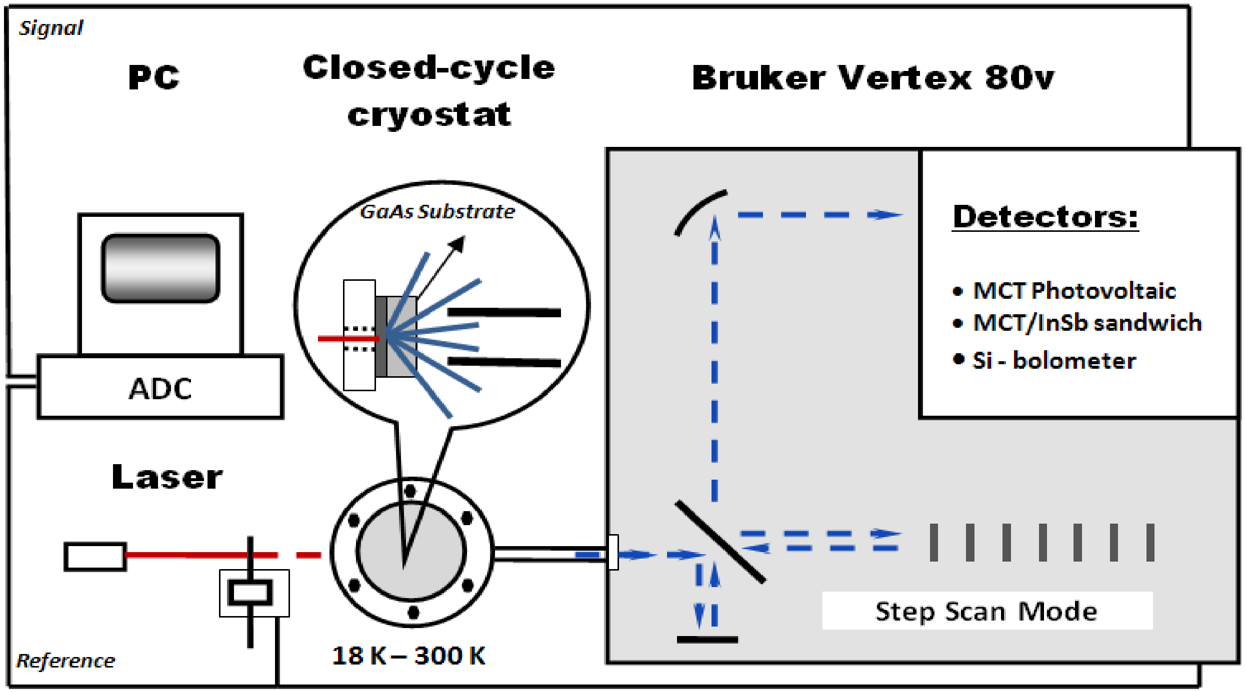
Experimental setup



PL spectra studies were carried out at T = 8 – 300 K in a closed-cycle cryostat optically connected to a Bruker Vertex 80v Fourier transform infrared (FTIR) spectrometer. The FTIR spectrometer was operated in the step scan mode. When studying PL, a continuous wave laser was used with excitation wavelength in λ_{exc} = 800 – 900 nm (Ti:sapphire laser Spectra Physics «Matisse-DR»). Excitation power was varied from 10 to 900 mW. The beam spot at the sample was ~ 3 mm in diameter. A special modulation technique was used, which is described in [Rev. Sci. Instrum. 2006, 77 (6), 063104], with the laser beam mechanically chopped. The modulation frequency was chosen according to detector response time, typically lying in the 200 Hz – 2 kHz range. Depending on the spectral range of the PL or signal, one of the following detectors was used: liquid N_2 cooled MCT Photovoltaic D317 (range 4800 – 850 cm^{-1}), MCT/InSb sandwich D318 (range 10000 – 600 cm^{-1}) or liquid He cooled silicon bolometer D211 (range 700 – 10 cm^{-1}). The detector signal was fed to the Stanford Research System SR560 amplifier and then recovered by a Stanford Research System SR830 lock-in amplifier. The data acquisition by the analog-to-digital converter (ADC) of the FTIR spectrometer was delayed by ~ 5 time constants of the lock-in amplifier after each step of the moving mirror of the spectrometer. For the SE studies the same measurement setup was used except for the lock-in amplifier. A pulsed optical pumping was used provided by either "SOLAR Laser Systems" KTP optical parametric oscillator emitting 10-ns-long pulses at 2.3 µm or CO2 laser with 10.6 µm wavelength at 100-ns-long pulse. A repetition rate for both sources did not exceed 10 Hz, therefore the SE signal from the detector was acquired directly by external high-speed ADC triggered with the synchronization pulse as described in [Appl. Phys. Lett. 2016, 108 (9), 092104].

Introduction

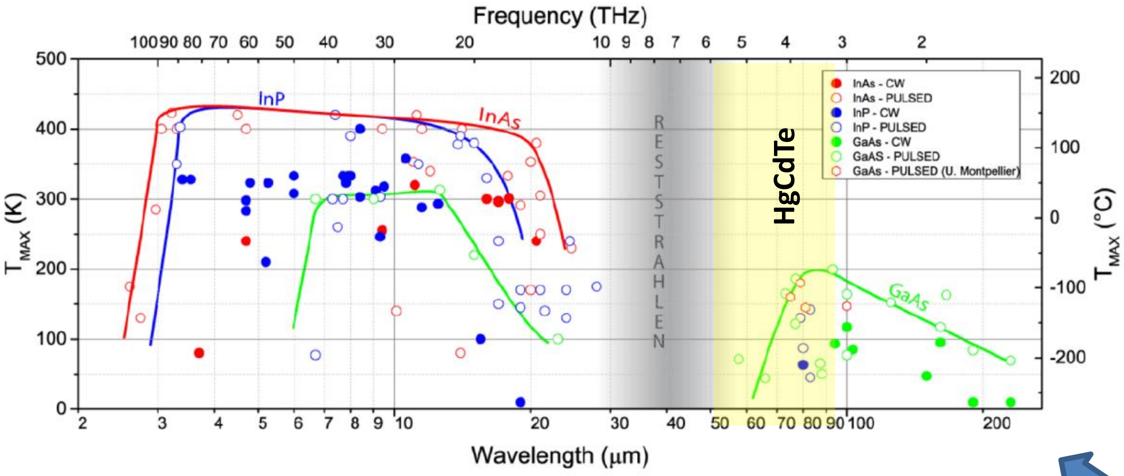


Fig. 1. Maximum operation temperature of quantum cascade lasers: state of the art.

Long wavelength InAs- based quantum cascade lasers

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The problem of developing compact far-IR wavelength emitters is one of the hottest topics in the applied physics. There is a spectral «gap» λ = 20 – 60 μm in which no quantum cascade lasers (QCLs) are available (except for several specific wavelengths near 20 μm) since the majority of QCLs are based on AIIIBV materials with strong lattice absorption in this spectral region. On the other hand, modern molecular beam epitaxy (MBE) delivers high quality HgTe/CdHgTe quantum well (QW) heterostructures. They allow tailoring the bandgap between hole and electron levels in QW to λ = 20 – 60 μm and have TO phonon frequencies lying lower than this range.

Laser emission in HgCdTe in the 2–3.5 μm range

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Journal of Crystal Growth 197 (1999) 529–536

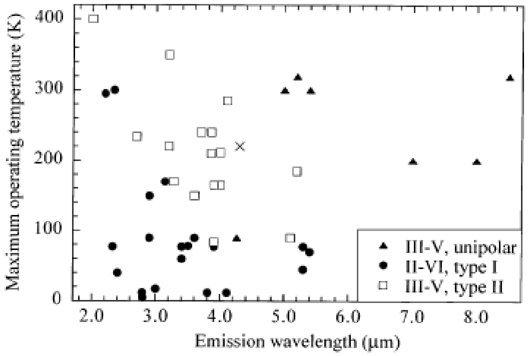

Fig. 9. Maximum, published operating temperatures for Hg-based, II–VI, type I lasers, Sb-based, III–V, type II lasers, and III–V, unipolar, quantum cascade lasers. Our samples are included. The cross indicates the recently published theoretical value for a HgTe/CdTe, short-period superlattice laser [21].

Previously, lasing in HgCdTe has been studied only in the short-wavelength part of the mid-infrared range (λ = 2 – 5 μm) As for the HgCdTe lasers with QWs, only emission near λ ~ 2 μm and ~ 3 μm was demonstrated under optical pumping.

Stimulated Emission at λ ~ 20 μm

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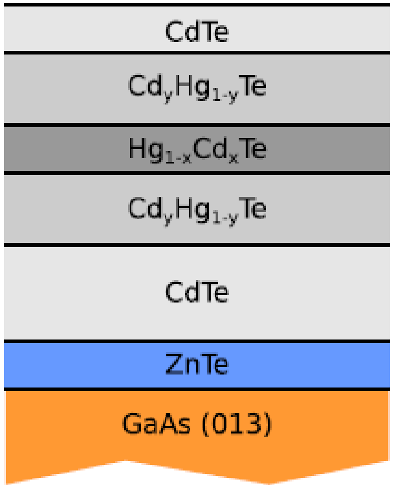
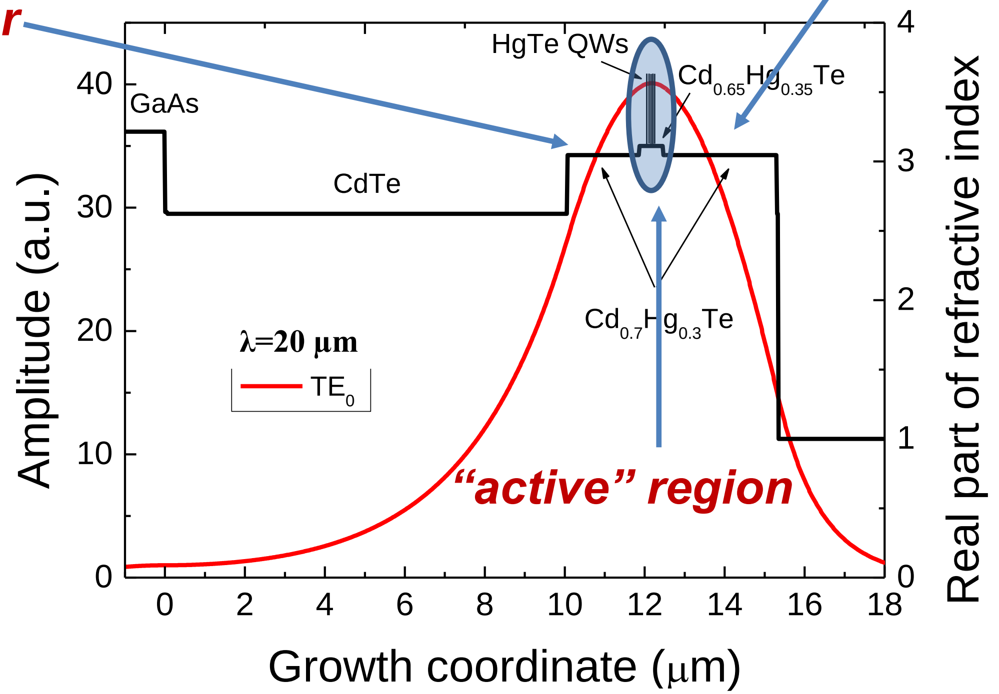


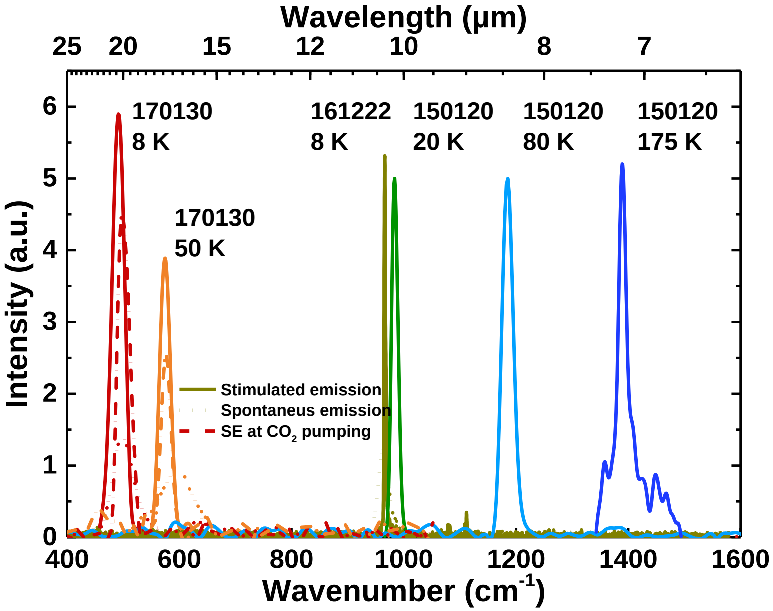
Structures under study were grown on GaAs substates with ZnTe and CdTe buffers in (013) direction. The typical parameters of the active part of the structures are shown on the picture.

waveguide layer

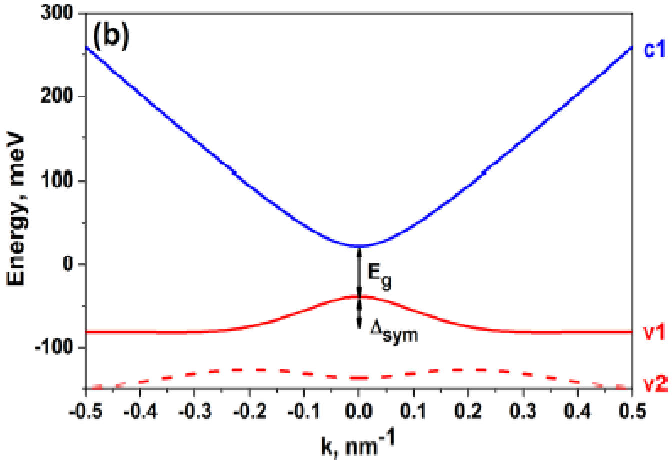
waveguide layer



"active" region



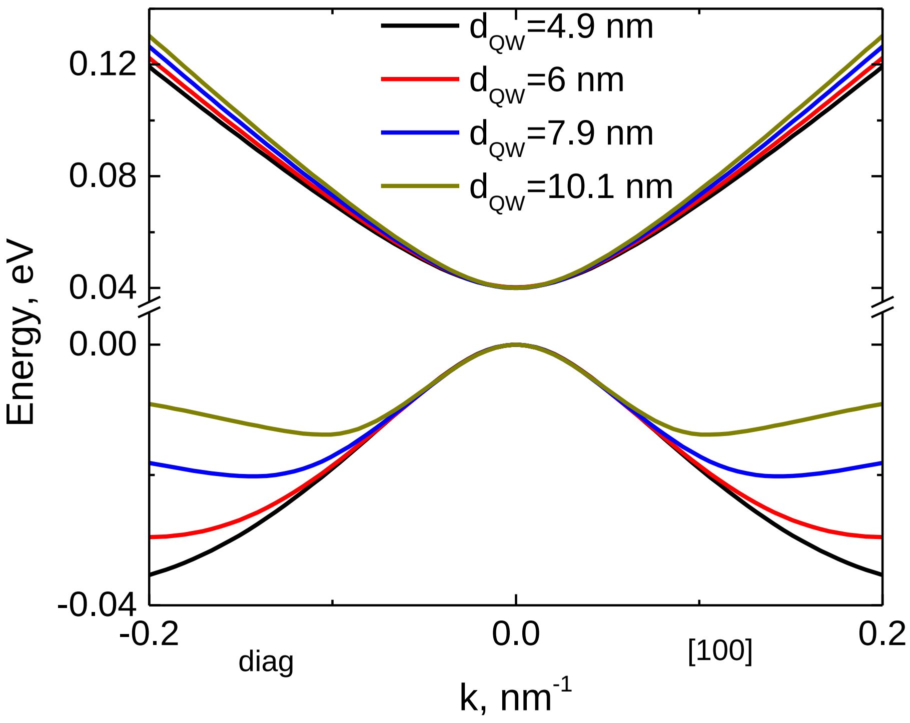
The SE and PL spectra for several samples under study



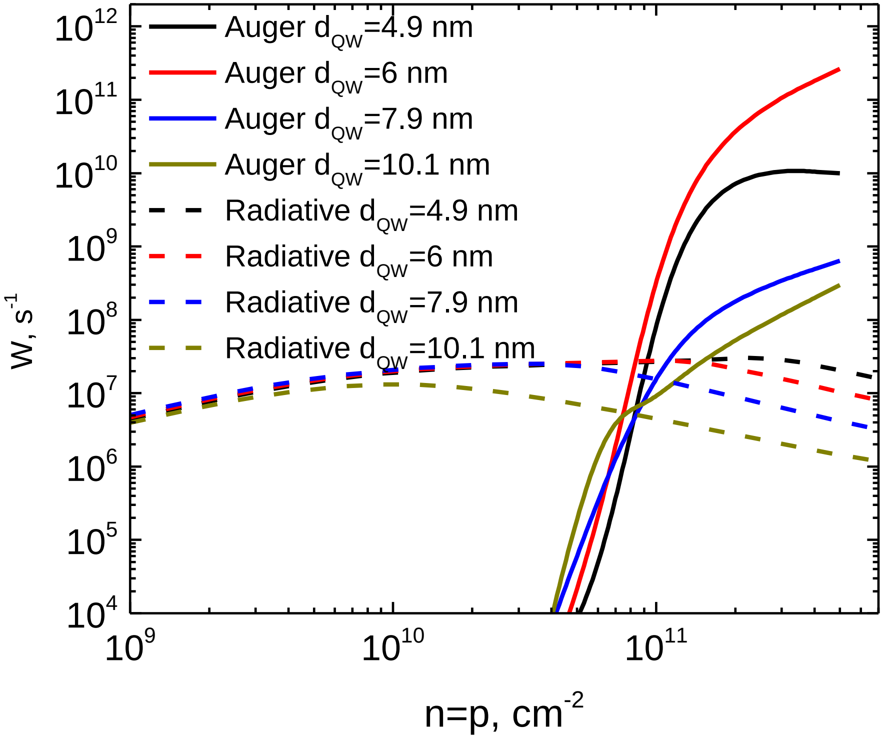
The calculated band spectrum for HgTe/HgCdTe heterostructure #170130 (T = 0K, d_{QW}=4.3 nm).

Recombination mechanisms for $Hg_{1-x}Cd_xTe/Cd_{0.7}Hg_{0.3}Te$ QWs

The question of the optimal QW parameters for laser action in the far-IR range is of great applied importance. To answer this question, we fix the band gap to 40 meV (λ = 31 μm) and study the effect of QW composition on Auger (AR) and radiative (RR) recombination. The probabilities of RR and AR were calculated for 4 QWs with Cd fractions of 0%, 3%, 6.5%, and 9% and thicknesses of 4.9 nm, 6 nm, 7.9 nm, and 10.1 nm, respectively.



Electronic spectra of 4 QWs at 8K. The direction of the wave vector, denoted by diag, corresponds to the diagonal between the directions [100] and [03-1].



Concentration dependences of the probability of AR and RR for 4 QWs at T = 8 K.

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Stimulated Emission at λ ~ 31 μm

To move into the longer wavelength region of the radiation, it is necessary to grow a very thick structure. Left top figure shows that for λ ~ 31 μm refractive index of GaAs is smaller than refractive index of CdTe and waveguide mode is localized. The reason for such behavior is the strong Reststrahlen band absorption in GaAs substrate. For optimum waveguide structure (left bottom figure) SE is obtained at λ ~ 24 μm at **cw** with threshold pump intensity 1 W/cm^2 of CO_2 laser.

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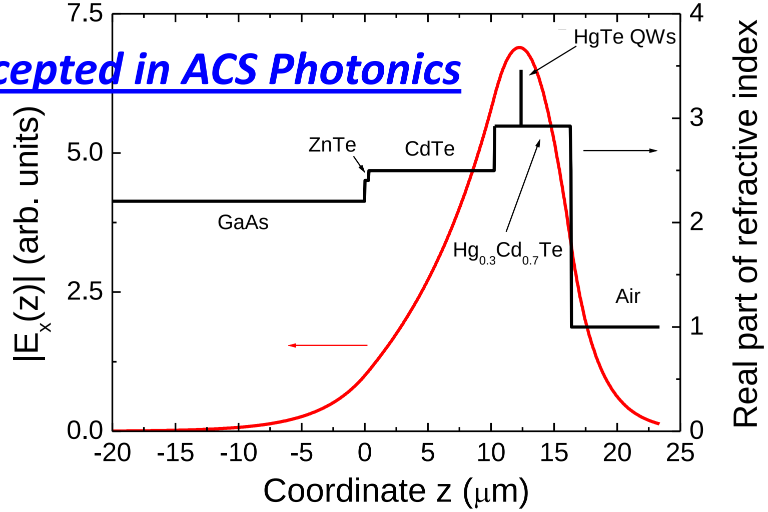
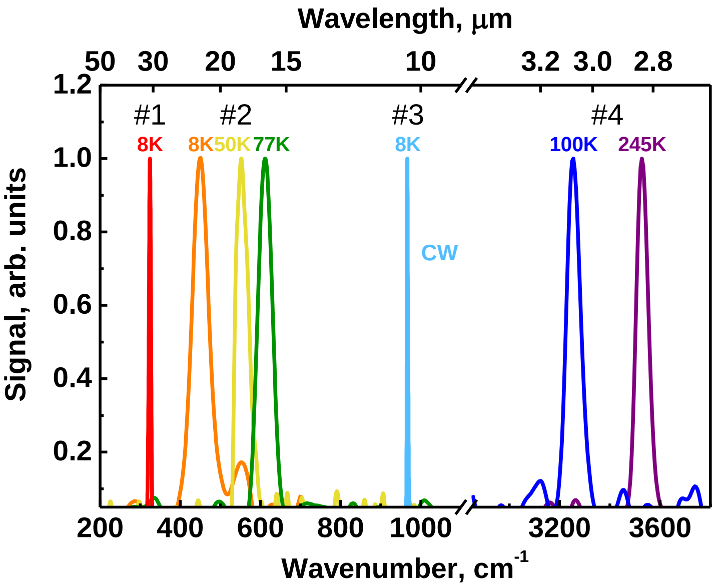
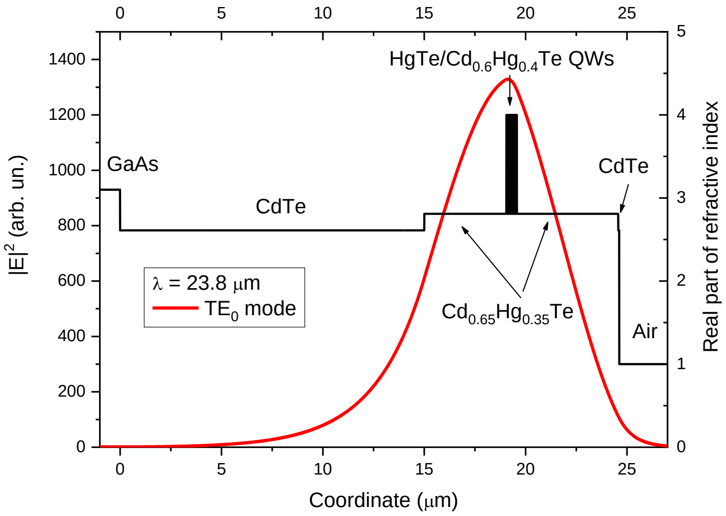
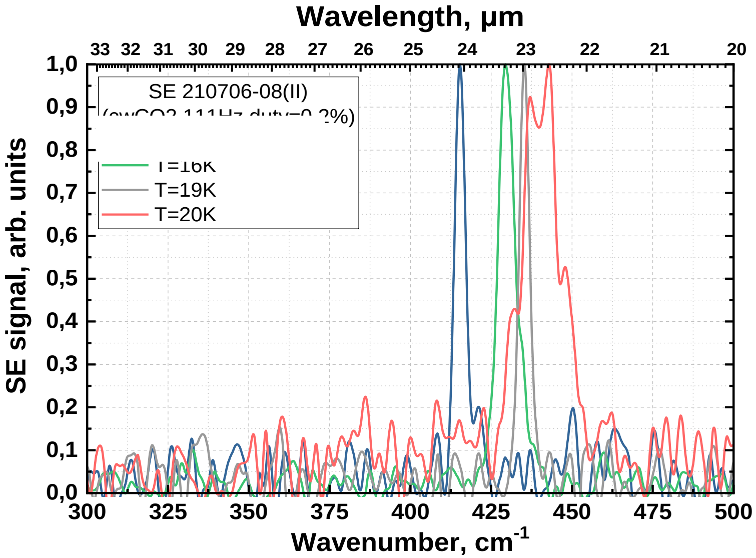




The SE spectra for several samples under study





Conclusions

- For waveguide HgTe/CdHgTe QWs structures we observed stimulated emission up to wavelength 31 µm. (before our investigations up to 5.3 µm).

- Localization of the waveguide mode at spectral range from 30 to 36 µm due to Reststrahlen band of GaAs substrate

- Auger recombination could be significantly suppressed in narrow HgTe/CdHgTe QWs due to quantum engineering design – Way to longwavelength and higher temperature

For optimum waveguide structure (left bottom figure) SE is obtained at λ ~ 24 µm at CW with threshold pump intensity 1 W/cm^2 of CO$_2$ laser.

- Problems not only in the Auger recombination, but also in the and two-phonon absorption in CdHgTe.