Pulse separation control for mode-locked far-infrared \( p \)-Ge lasers

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Active mode locking of the far-infrared \( p \)-Ge laser giving a train of 200 ps pulses is achieved via gain modulation by applying an rf electric field together with an additional bias at one end of the crystal parallel to the Voigt-configured magnetic field. Harmonic mode locking yields a train of pulse pairs with variable time separation from zero to half the roundtrip period, where pulse separation is electrically controlled by the external bias to the rf field. © 1999 American Institute of Physics. [S0003-6951(99)02002-1]

Recent progress on \( p \)-Ge far-infrared lasers (50–140 cm\(^{-1}\)) includes increased duty cycle to 3%,\textsuperscript{1} use of permanent magnets\textsuperscript{2} and closed cycle refrigerators\textsuperscript{3} to eliminate liquid cryogens, deep donor doping\textsuperscript{4,5} to separate impurity absorption from the gain spectrum, and active\textsuperscript{6–8} and passive\textsuperscript{9} mode locking. Motivation for these studies is a lack of compact solid-state lasers between millimeter and infrared wavelengths and increasingly important applications for THz radiation. This letter reports harmonic\textsuperscript{10} active mode locking with important new observations concerning electrical control of gain modulation and pulse separation.

Far-infrared \( p \)-Ge lasers operate in a wavelength range from 70 to 200 \( \mu \)m. Usual \( p \)-Ge lasers generate far-infrared pulses with a few \( \mu \)s duration and peak power of 1–10 W. Stimulated emission occurs on direct optical transitions between light- and heavy-hole valence subbands in bulk \( p \)-Ge at liquid helium temperatures in strong crossed electric and magnetic fields. Population inversion is built up at certain magnetic fields. Population inversion is built up at certain liquid helium temperatures in strong crossed electric and magnetic fields.

With this setup, generation of two pulses per roundtrip (harmonic mode locking) is achieved for the first time, and electrical control of the time delay between the pulses is demonstrated.

Single-crystal, Ga-doped, \( p \)-Ge with a concentration of \( 7 \times 10^{13} \text{ cm}^{-3} \) was cut into a rectangular bar with a cross section of \( 5 \times 7 \text{ mm}^2 \) and a length of 84.2 mm. Ohmic contacts were made by Al evaporation and subsequent annealing at opposite lateral sides of the crystal (\( 5 \times L \text{ mm}^2 \)), and then covered with In. The crystal ends were polished parallel to each other within 1 arc minute accuracy and two external copper mirrors were attached to them via 20-\( \mu \)m teflon film (Fig. 1). Crystals were immersed in liquid helium at 4 K. Magnetic fields up to 1.4 T were applied in Voigt geometry using a room temperature electromagnet (Walker Scientific HF-9H) external to the cryostat (Janis SDT). Electric field pulses \( E_{HV} \) are applied from a low duty-cycle thyatron pulser. The field orientations were \( E_{HV} \parallel[1\bar{1}0] \) and \( B \parallel[112] \). Radiation was conducted out of the top of the cryostat using a brass light pipe sealed with a teflon lens.

For local regulation of the orientation and fast modulation of \( E_{HV} \), small additional contacts with a length of \( \sim 4 \) mm were placed perpendicular to the main contacts at one end of the crystal (Fig. 1) for providing an additional electric field \( E_L \parallel B \). In this way, the orientation of \( E_{HV} \) can be regul-

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{p-Ge_laser_diagram}
\caption{Diagram of \( p \)-Ge laser crystal with contacts, end mirrors, applied fields, and rf electric field modulation at one end.}
\end{figure}
The additional bias to the rf signal is supplied by dividing the potentials protect HV and rf systems from each other. The additional used to improve impedance match to the dynamic load and measurements were verified by direct observation of the rf voltages monitor forward and reflected rf power. Power measurement of this signal to a Stanford Model SR620 frequency oscillator delivers about 0.3 W continuous wave (cw) signal that is frequency stable within a few tens of kHz. A directional coupler feeds a fraction of this signal to a Stanford Model SR620 frequency counter. The main part goes to a Minicircuits Model 15542 bias-T. A Picosecond Pulse Labs 5840 amplifier with 10 GHz bandwidth boosted signals, which were then recorded on a Tektronix SCD5000 transient digitizer with 4.5 GHz analog bandwidth, 200 G-samples/s, and 11 bits vertical resolution (2 mV quantization steps).

Figure 3 shows the output of the actively mode-locked laser for different settings of the external bias (U1 – U2). The cavity roundtrip time of our 84.2-mm-long sample is calculated to be 2.20 ns giving a roundtrip frequency of νrt = 453.6 MHz. Experimentally, a resonance is found at 453.8 MHz, where the applied rf is unable to extinguish lasing, indicating mode locking. Apparently, a small change in the additional bias to the rf modulation field now has a significant influence on the output of the mode-locked laser, which is now periodic at the roundtrip frequency. Increasing the offset causes the mode-locked pulses to broaden and eventually split into two. A further increase in bias causes further separation of the pulses within each pair.

This behavior is explained in Fig. 4, which shows a schematic of gain modulation and the resulting pulse train due to an rf field for three different rf offsets. In each sub-figure, the upper left curve shows the decrease of gain due to the small E_L field along the magnetic field direction. The upper right curve shows the gain modulation that results from the biased rf signal shown in the lower left corner, while the lower right bold curve shows the expected output pulse train.

When E_L [i.e., the voltage U1 – U2 in Fig. 2(a)] is increased, the additional contacts is applied at the peak of the gain versus E_L curve [Fig. 4(c)], gain modulation occurs at twice the rf frequency, and the double pulse output from harmonic mode locking is expected. Moving the bias away from the point of maximum gain, the gain is more and more modulated at the single rf frequency, and the pulses in each pair...
FIG. 4. Explanation of bias effects and pulse-separation control. The left curve plots gain vs external bias. The right curve shows the modulation of the gain vs time, when the rf field is applied at the bias level indicated. The pulse train expected to result is also indicated. The three situations: (a) large offset modulation far from peak of gain vs $E_L$, (b) small offset modulation close to peak of gain vs $E_L$ curve, and (c) zero offset modulation at peak of gain vs $E_L$ curve mimic the experimental results in Fig. 3.

A comparison of Figs. 3 and 4 shows that the experimentally observed output without any external biasing is connected to a situation where the rf modulation is already offset from the top of the gain versus $E_L$ curve [Fig. 4(a)], and external biasing is necessary to bring the rf modulation to the top of this curve [Fig. 4(c)]. The “intrinsic” voltage offset can be shown to be due to charging of the laser crystal because of anisotropy of the hot hole distribution in the $k$ space. For the same reason as here, external biasing was shown to enable optimization of the gain for the normal microsecond-pulse operation (without rf), and there was significant improvement in the output of an actively mode-locked $p$-Ge laser with $\nu_{rf} = \nu_{RT}^2$. Upon moving to the top of the gain versus $E_L$ curve, the total gain is optimized in the first case, while in the second the optimal situation for mode locking at twice the rf frequency is reached. A further discussion of the influence and physical origin of this offset is given in Ref. 12.

Thus, active mode locking of the $p$-Ge far-infrared laser with $\nu_{rf} = \nu_{RT}$ results in the generation of an output train of double far-infrared pulses with <200 ps duration (harmonic mode locking). By changing the external bias to the rf modulation field the temporal separation for a pair of mode-locked pulses can be controlled. The ability to generate a train of double pulses with electrically controllable pulse separation suggests that mode-locked $p$-Ge lasers may have promise for telemetry in special applications.

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