

Effect of intracavity interface on p-Ge laser emission dynamics

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Abstract: Temporal dynamics of the far-infrared p-Ge laser emission and its dependence on the laser cavity design have been studied in order to investigate the possibility of using intracavity elements for the purpose of active and passive mode locking. The positive result for mode locking with intracavity elements is that the laser modes are still defined by the entire cavity including the insert, although the interface influences the relative intensities of the various modes.

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The far-infrared p-Ge laser, operating in the spectral range $50\text{-}140\text{ cm}^{-1}$ ($70\text{-}200\text{ }\mu\text{m}$ or $1.5\text{-}4.2\text{ THz}$) [1], has the potential to generate picosecond pulses of far-infrared radiation due to its broad gain spectrum [2,3]. Rapid progress has been realized recently in active mode locking via rf gain modulation at one end of the laser rod in the Voigt configuration of applied fields [4-7]. The mechanism of stimulated emission of p-Ge lasers is based on direct optical transitions between light and heavy hole valence subbands in bulk p-Ge (Fig. 1) in strong crossed electric and magnetic fields, when the crystal is cooled

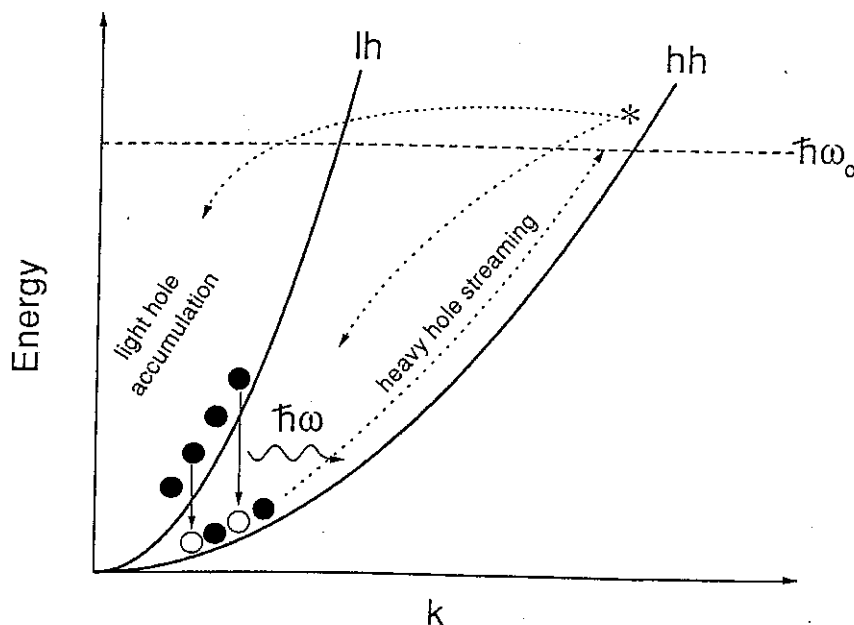


Fig. 1. Pumping mechanism of the p-Ge laser. Solid parabolas represent the light- (lh) and heavy-hole (hh) bands. The dotted-lines represent heavy holes accelerated beyond the optical phonon energy ($\hbar\omega_0$), then scattered back to the heavy- or light-hole band. Accumulation of hot light-holes is indicated together with downward transitions and THz photon emission.

to liquid helium temperatures. The population inversion builds up for certain ratios of electric and magnetic fields, when light holes are accumulated on closed trajectories below the optical phonon energy, while heavy holes are strongly scattered by optical phonons. The electric field is applied through ohmic contacts covering two opposite sides of the rectangular parallelepiped-shaped crystal. For active mode locking, additional small ohmic contacts have been fabricated near one of the laser crystal ends and an rf electric field is applied to them in a direction along the magnetic field, perpendicular to the main electric field. This rf field accelerates light holes along the magnetic field beyond the threshold for optical phonon emission, thus decreasing their lifetime and modulating the gain. If the modulation frequency of the gain is equal to the round trip frequency of the laser cavity, mode-locked pulses as short as 100 ps (FWHM) can be observed [4-7]. However, this mode-locking scheme is difficult to optimize since performance depends critically on placement and geometry of rf contacts, which are difficult to change once established.

A more convenient active mode locking scheme might involve use of electro-optic intracavity modulators. To obtain even shorter pulses, passive or hybrid mode-locking schemes should be considered, where an intracavity saturable absorber, separate from the gain medium, is used. Indeed, evidence for passive mode locking with such inserts has been found [8]. A disadvantage of such combined cavities is the additional reflections and loss at intracavity interfaces between optical elements. Because of the high index of refraction of Ge, an added cavity element needs to be in direct contact with the Ge crystal and have an index as close as possible to that of Ge. The purpose of this paper is to investigate the effects on the laser dynamics of a simple intracavity element for values of gain, mode structure, etc. specific for p-Ge lasers. A Si spacer is chosen since Si is readily available and has low far-infrared absorption, which is important since the p-Ge laser is a low gain medium. Also, the refractive index of Si is sufficiently close to that of Ge that only 1% reflection is expected at the Si/Ge interface for good optical contact.

The active Ga-doped Ge crystal with $N_A \approx 7 \times 10^{13} \text{ cm}^{-3}$ has dimensions $5 \times 7 \times 50.2 \text{ mm}^3$ and is cooled by immersion in liquid helium at 4 K. Electric field pulses of $2 \mu\text{s}$ duration are applied along the [110] crystal axis via ohmic contacts covering the $5 \times 50.2 \text{ mm}^2$ sides. The magnetic field, created by an external room temperature electromagnet, is applied along [001] in Voigt geometry. The crystal ends were polished parallel to each other within 1' accuracy and two external copper mirrors were attached to them via $20 \mu\text{m}$ teflon film (to prevent electrical breakdown). For the composite cavity, as shown in Fig. 2, a polished Si spacer ($n_{\text{Si}} = 3.382$) with thickness 8.4 mm was inserted between one end of the Ge rod ($n_{\text{Ge}} = 3.926$) and the 7 mm diameter copper back mirror. The laser radiation propagates along the long crystal axis [1-10], is conducted out of the cryostat using a brass light pipe, is detected after a teflon lens with a fast whisker-contacted Schottky diode (1T17(82), University of Virginia), and is recorded on a transient digitizer (Tektronix SCD5000) with 4.5 GHz bandwidth.

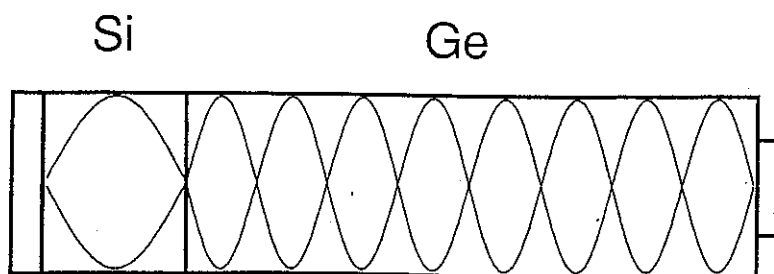


Fig. 2. Construction of the composite Si/Ge cavity. Modes with nodes at the Si/Ge interface will experience the smallest loss. Wavelengths are exaggerated.

Figure 3(a) shows the periodic temporal structure for one laser shot without the insert. The main oscillation period equals the calculated roundtrip time $\tau_1 = 2 n_{Ge} L_{Ge} / c = 1315$ ps. The periodic pattern results from superposition of a series of axial modes with frequency difference equal to the cavity round trip frequency. The pattern of mode interference within one roundtrip period depends on the initial random phase distribution of the modes, which differs for each laser shot. The data in Fig. 3(a) were chosen for presentation especially because of the relatively large intensity oscillations. When the spacer

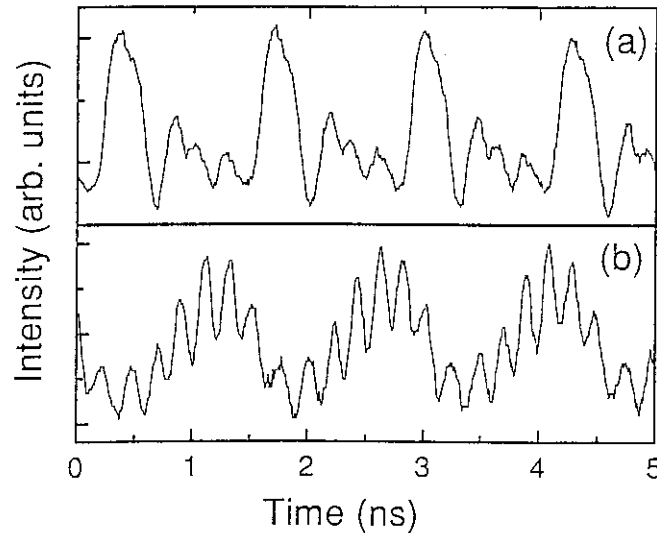


Fig. 3. Transient recording of p-Ge laser emission (a) without and (b) with a Si spacer in the cavity.

is inserted in the cavity, higher frequency components become more prominent, as shown in Fig. 3(b). Now each shot clearly reveals a high frequency structure superimposed on lower frequency oscillations. The calculated roundtrip time of the full cavity (Ge rod plus Si spacer) is $\tau_2 = (2 / c)(n_{Ge} L_{Ge} + n_{Si} L_{Si}) = 1504$ ps. The observed period of fast oscillations is $\tau_3 = 215$ ps, which differs from the calculated Si-spacer roundtrip time $\tau_4 = 2 n_{Si} L_{Si} / c = 190$ ps for internal reflections within the Si. The observed τ_3 in Fig. 3(b) is a harmonic of τ_2 , i.e. $\tau_3 = \tau_2 / q$, where q is 7, which means that the eigenmodes of the coupled laser cavity are still defined by the full resonator despite reflections and/or loss at the Si/Ge boundary. The various periods are summarized in Table 1.

Table 1. Summary of round trip times and frequencies

τ_1	round trip time in Ge	1315 ps	760 MHz
τ_2	round trip time in Ge + Si	1504 ps	665 MHz
τ_3	observed fast oscillation period	215 ps	4.65 GHz
τ_4	round trip time in Si	190 ps	5.26 GHz

The average Fourier transform of a series of data such as in Fig. 3(a) and (b) are presented in Fig. 4(a) and (b). For the laser without an insert, in Fig. 3(a), harmonics (numbered) of the fundamental round-trip frequency 760.5 MHz ("1") are observed up to the seventh. Harmonics 5 and up are already attenuated by the 4.5 GHz bandwidth of the electronics. For the laser cavity with a Si spacer, in Fig.

4(b), harmonics up to the 9th are observed, and their spacing is smaller than in Fig. 4(a) owing to the smaller round-trip frequency 664.7 MHz for the combined cavity. Compared to Fig. 4(a), the 2nd and 3rd harmonics are strongly suppressed, and the higher harmonics are relatively more pronounced.

Harmonics of the fundamental round trip frequency occur in Figs. 4(a) and 4(b) because of beating between different pairs among the ensemble of evenly spaced axial modes [8]. These modes are defined by $f_p = p / \tau_2$, where τ_2 is the roundtrip time for the full cavity and p is an integer. The redistribution of energy in the frequency spectrum of mode beating caused by the insertion of the optical spacer (Fig. 4(b)) can be explained in terms of losses and scattering at the Si/Ge interface and competition between modes in the active Ge crystal. Small loss modes will be more prominent in the laser output. Losses can occur from interface absorption or scattering. Losses are expected to be largest for those modes having a large amplitude of the oscillating electric field at the interface and smallest for modes with interface nodes as shown schematically in Fig. 2. Small loss modes are therefore $f_q = q / \tau_4$, where q is as close as possible to an integer. Thus, minimum loss combined cavity modes occur when $f_p = f_q$ or $p = (\tau_2 / \tau_4)q = 7.92 q$. The requirement for low loss that q be nearly integral means that periods $\tau_2/8$ should be prominent in transient recordings of the composite laser.

As an example, for a typical mode number in the full cavity $p = (1.504 \text{ ns})(1 \text{ THz}) \approx 1505$, the number of modes in the spacer q has nearly the integer value 190. The next integer p -value for which q is close to an integer ($q \approx 191$) is $1513 = 1505 + 8$. Hence beat frequencies of the 8th harmonic of the fundamental full cavity roundtrip frequency should be most prominent in the transient recording. This occurs at 5.3 GHz. Instrumental bandwidth makes the 7th harmonic appear as the peak, as in Fig. 4(b).

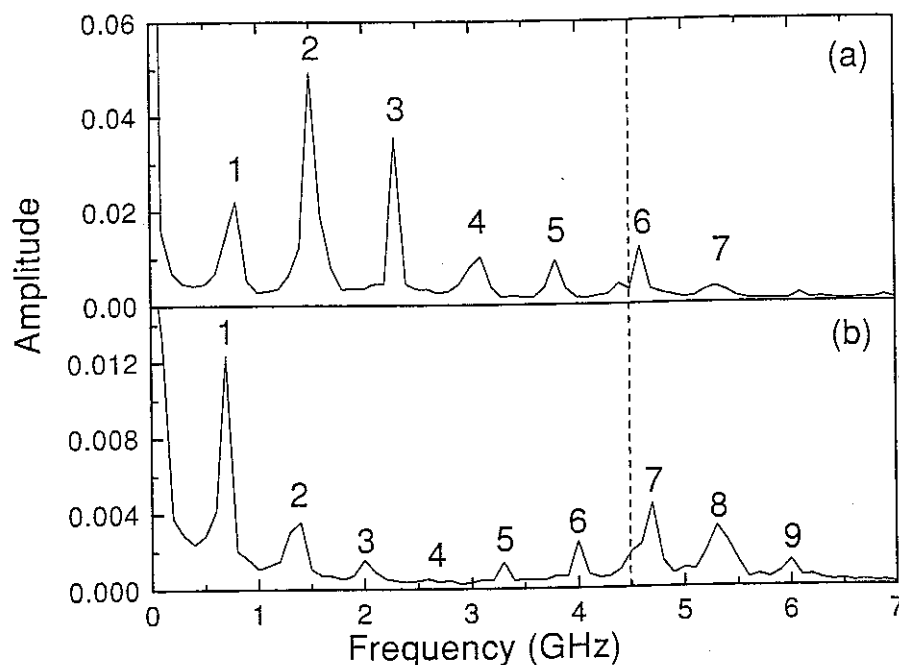


Fig. 4. Fourier transform of transient records for p-Ge laser emission (a) without and (b) with a Si spacer in the cavity. The 4.5 GHz instrumental bandwidth is shown by the dashed line.

These arguments are supported by a simple mathematical model. The intensity after n passes through the composite Si/Ge cavity in a linear regime of laser emission development is

$$I_n = I_0 [e^{\alpha L} - \delta \cos^2(k_1 L)]^n \quad (1)$$

The active Ge crystal has length L and gain coefficient α . Scattering or absorption at the Si/Ge interface with loss coefficient δ is taken to be proportional to the squared amplitude of the oscillating electric field of certain modes (k_1) at the interface. The wavenumber k_1 in the Ge cavity for modes with allowed frequencies for the combined cavity is $k_1 = 2\pi n_{Ge} p / c \tau_2$. The time dependence caused by beating between the pair of modes p and $p+q$, is given by

$$|E|^2 \approx I_n(p) + I_n(p+q) + \frac{2I_{n/2}(p)I_{n/2}(p+q)}{I_0} \cos(2\pi q t / \tau_2) \quad (2)$$

where n has been taken to be even without loss of generality. The third term represents beat oscillations with frequencies q / τ_2 , which can be observed with our detection electronics not beyond about $q=10$. For a given q , the amplitude of the beat oscillation depends on the mode number p . Since hundreds of modes can oscillate simultaneously, the spectrum of observable beats $y(q)$ is found by averaging (summing) the amplitude over many p values,

$$y(q) = \sum_{p=1500}^{p=1600} I_{n/2}(p) I_{n/2}(p+q) \quad (3)$$

Fig. 5 shows the calculated beat spectrum for the composite Si/Ge cavity using example model parameters $\delta = 0.04$, $\alpha = 0.1 \text{ cm}^{-1}$, and $n=400$. The eighth harmonic of the fundamental frequency is most prominent and the fourth harmonic is strongly suppressed, which agrees qualitatively with the experimental data in Fig. 4(b). In the above model the influence of multiple reflections in the silicon is assumed to be negligible. Incorporation of coupled-cavity effects [9] requires more detailed modeling [10], is expected to yield the same overall picture, and only slightly modifies the interpretation of the loss parameter δ in the current model.

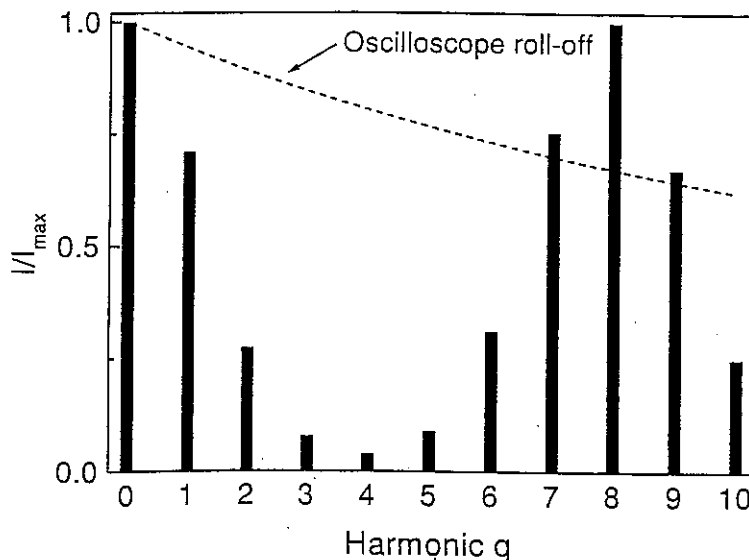


Fig. 5. Modeled beat spectrum for the p-Ge laser with Si intracavity spacer. Roll-off for the 4.5 GHz instrumental bandwidth (taken as a first order low pass filter for simplicity) is shown by the dashed line.

The cavity effects observed here are important for the development of passive or active mode locking of the p-Ge laser with coupled cavities, where a saturable absorber or gain modulator may be inserted inside the p-Ge laser cavity. Although the optical spacer might cause some increase in the mode-locked pulse width via mode suppression, the positive outcome for the possibility of mode locking with added intracavity elements is that the laser still can generate a train of pulses with a repetition rate defined by a harmonic of the main round trip frequency, even though the optical lengths of the optical spacer and full cavity do not have an integer ratio.

Acknowledgments

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