Improving the Transverse Mode Structure and the Stability of the p-Ge THz Laser.

J. N. Hovenier[1], E. E. Orlova[1,2], T. O. Klaassen[1] and W. Th. Wenckebach[1],

[1]Department of Applied Physics, Delft University of Technology, The Netherlands.
[2]Institute for Physics of Microstructures, RAS, Nizhny Novgorod, Russia.

The p-Ge THz laser with flat external cavity mirrors exhibits strong intensity modulations at frequencies in the 8-80 MHz range, resulting from beating of transverse modes. A theoretical description of the mode structure of this cavity is given. Results compare well with experimental data on beat frequencies and far field beam profiles. A cavity with a back mirror reduced to about 70% of the end face surface is found to leads to an effective suppression of the mode beatings. A strongly improved pulse to pulse stability of the output and a much better far field beam shape is observed.

Introduction.

The p-Ge laser provides THz emission in the of 70-200 μm wavelength range [1]. In order to achieve maximum output power and a good beam profile, we use a metal mesh as output coupler [2]. This however is found to cause strong fluctuations in the output power, resulting from the beating of transverse modes in the cavity. We give a concise description of the observed beat frequencies and measured beam profiles and propose the use of a back mirror of reduced size to suppress higher order modes.

The present (Voigt configured) Ge:Ga laser crystal is a rectangular parallelepiped with $a \times b \times l = 5 \times 7 \times 49.5$ mm. The mesh and back mirror are pressed against the 5×7 crystal end faces. The $a \times l$ facets are completely covered by the electrical contacts for the electrical excitation field **E** // (1,-1,0). The magnetic field **B** // (1,1,-2) is perpendicular to both **E** and the long axis of the crystal. At the $b \times l$ facets, near the mesh out coupler, 1×10 mm electrodes for active mode locking are placed [3][4][5].

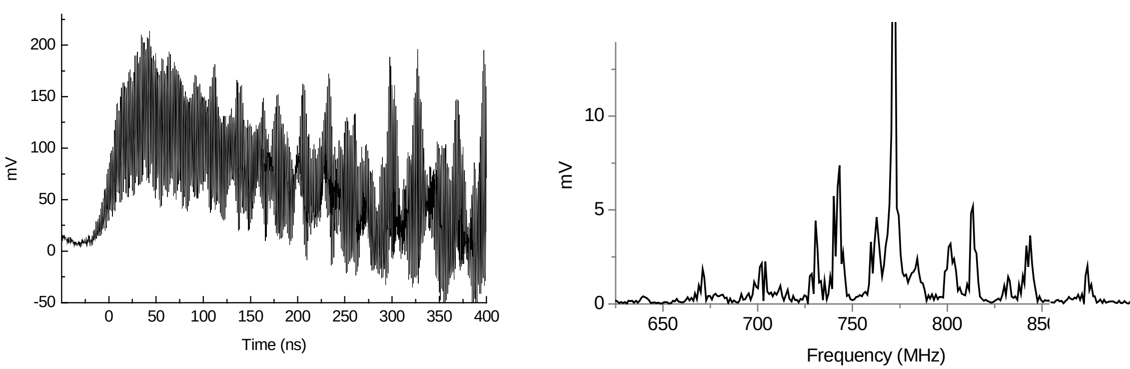


Fig. 1. Typical pulse shape for a cavity with large back mirror for B= 0.9 T ($\lambda \approx 90$ - 110 μm) . The Fourier spectrum shows the presence of a large number of modulation frequencies

Mode structure with a large back mirror: experiment.

In fig.1. a typical pulse shape is shown, using a 5×7 mm back mirror. The Fourier spectrum shows modulations at 6, 11, 31, 40, 61, 69, 73 and 770 MHz; the latter being the cavity round trip frequency. To obtain additional information concerning the transverse modes present, far field beam patterns were measured. In fig. 2 two intensity contours are given as a function of *x/z* and *y/z*, where *z* is the axial distance from the laser crystal and *x* // *a* // **B** and *y* // *b* // **E**. The *x/z* and *y/*x scales represent the far field divergence angles of the laser beam. The mode structure – Low order modes in low field, high order modes in high field – is visible.

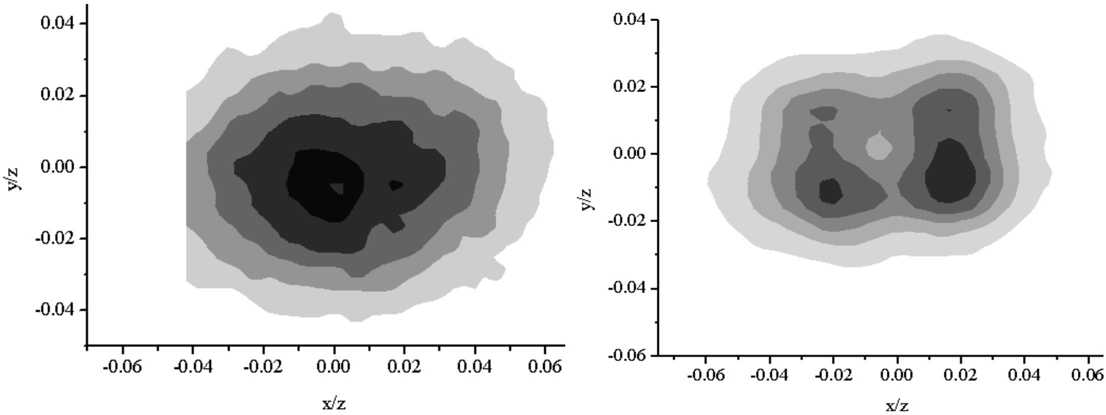


Fig. 2. Experimental far field beam profiles for a cavity with large back mirror.
a. B=0.50 T ($\lambda \approx$ 175μm); b. B=1.32 T ($\lambda =$ 90 – 110 μm)

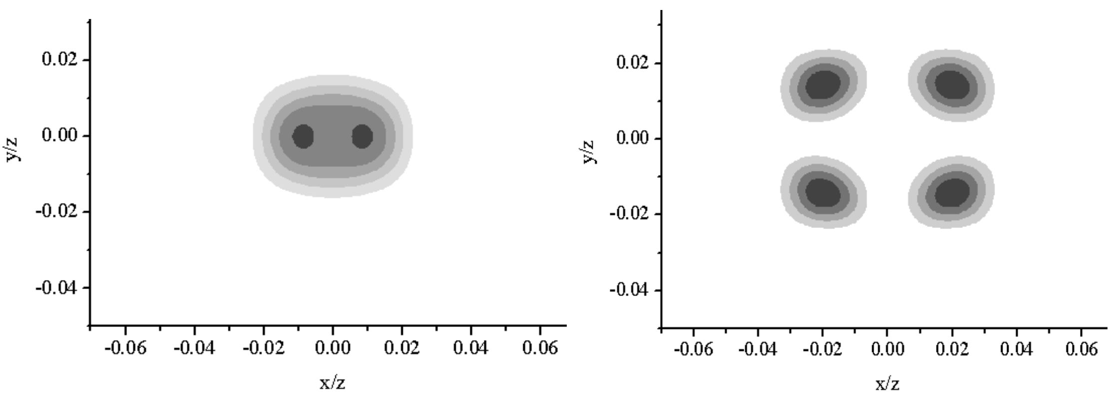


Fig. 3. Theoretical far field beam profiles for a cavity with large back mirror.
a.. Mixture of (1,0) and (1,1) modes at λ = 175μm; b. (2,2) mode at λ = 100μm

Mode structure with a large back mirror: theory.

The field in the resonator is described by the Maxwell equations for a dielectric medium (n=3.925) with boundary conditions $E_\tau = 0$ for the $a \times l$ facets (ideally conducting surfaces) and E_τ and H_τ continuous across the $b \times l$ facets.

The field distribution for electric (H_z =0) and magnetic (E_z =0) waves is given by the electric and magnetic Hertz vectors parallel to *z* the axis with the complex amplitudes Π^E and Π^H:

$$\Pi^{E,H} = \Pi_0^{E,H} \sin(k_z z)\left(e^{ik_x x} \mp (-1)^L e^{-ik_x x}\right)\left(e^{ik_y y} \mp (-1)^M e^{-ik_y y}\right)$$

The boundary conditions result in $k_y = M\pi/b$, $k_z = N\pi/l$ and $k_x \approx L\pi/a$ (for $k_x / k\sqrt{n^2-1} \ll 1$). For k_x, $k_y \ll k$, the mode frequencies are then given by $\nu = \frac{ck_z}{2\pi n}\left(1 + \frac{1}{2}\left(\frac{k_t}{k_z}\right)^2\right)$ with $k_z \cong kn = \frac{2\pi n}{\lambda}$ and $k_t^2 = k_x^2 + k_y^2$.

The wavelength dependent frequency *differences* between some of the transverse modes are presented in fig. 4b. Using these data and the observed beat frequencies, the presence of many low order *(L,M)* modes can be identified. Calculated far field profiles for a mixture of the (1,0) and the (1,1) modes at λ = 175μm (fig. 3a) and for the (2,2) mode at λ = 100 μm (fig. 3b) show a good agreement with the patterns in figs. 2a and b. in terms of overall beam divergence and intensity maximums.

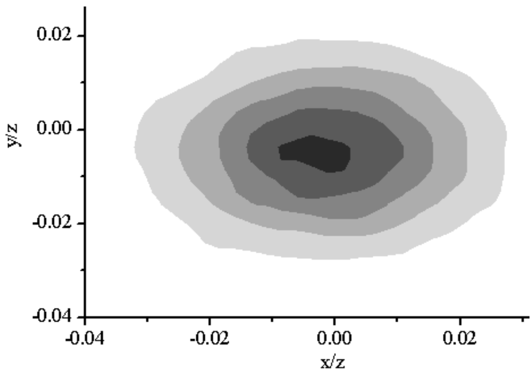


Fig. 4a. Far field beam profile for cavity with 4.2×5.8 mm back mirror (B=0.5 T, λ= 175 μm).

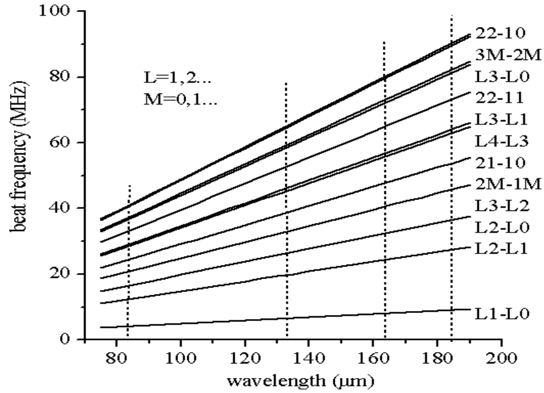
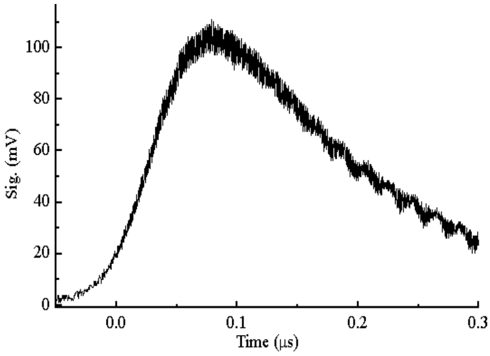


Fig. 4b.Wavelength dependent frequency differences between transverse modes for big back mirror

Mode structure of resonator with small back mirror: experiment

To reduce the instability of the laser output due to mode beating, and improve the beam quality, we investigated the possibility to increase the losses for the higher order transverse modes by reducing the size of the back mirror.

For the experimental verification a 4.2×5.8 mm back mirror has been chosen, covering about 70% of the end face surface. In low field only a very weak mode beating is observed, see fig. 5a. The pulse to pulse stability has improved considerably compared to that with a large back mirror. In fig. 4a the experimental beam pattern is seen to be much less divergent than that in fig. 2a. In high field laser action is absent with small back mirror most probably due to the big losses for higher order modes.



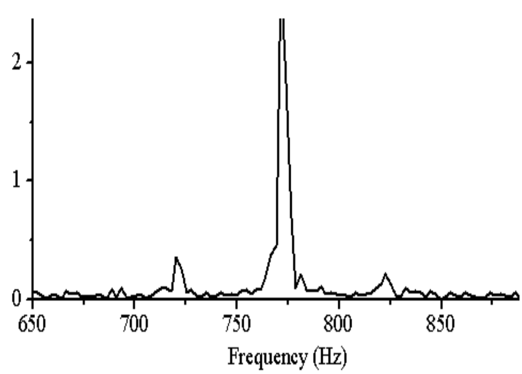


Fig. 5a. Pulse shape and Fourier spectrum for B=0.5 T (λ ≈ 175μm) for cavity with 4.2×5.8 mm back mirror.

Fig.5b FFT: 770 MHz oscillations, only weak beating in the tail of the laser pulse is observed.

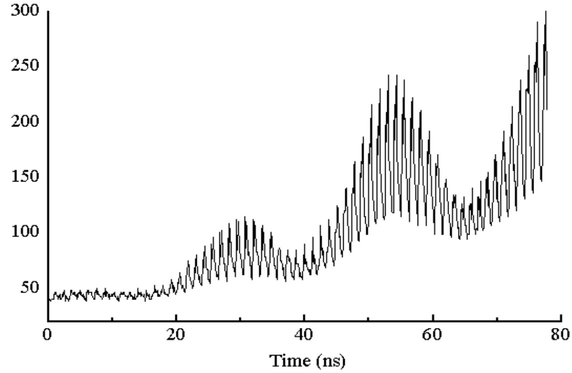


Fig. 6. Start of laser action under mode locking conditions with a big back mirror. (B= 0.5T)

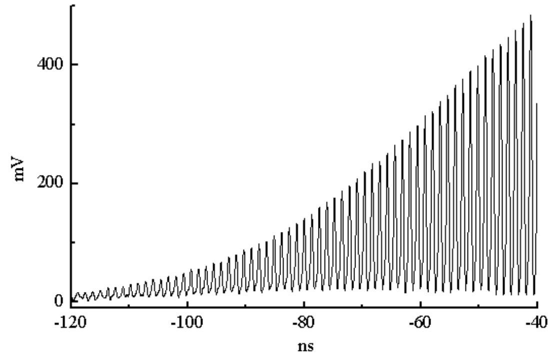


Fig. 7 Start of laser action at B=0.5 T under mode locking conditions for a cavity with small back mirror. A smooth increase of micro pulse intensity is observed.

Conclusion

The transverse mode structure of the p-Ge THz laser with a cavity consisting of a large back mirror and metal mesh out couple mirror has been studied. The experimental results on beat frequencies and far field beam profiles are well described by a simple model for transverse waveguide modes.

Decreasing the size of the back mirror leads to an effective suppression of higher order modes, resulting in much better (sub- 100ps) micro pulse shapes and stable macro pulse trains under active mode locking conditions figs. 6,7. The peculiar field dependence of the mode structure found in this specific laser crystal is not yet understood.

References

[1] E. Gornik and A. A. Andronov, Eds., *Optical. Quantum Electronics*. vol. 23, Special issue on far infrared semiconductor lasers, London: Chapman and Hall, 1991.

[3] T.O. Klaassen, J.N. Hovenier, W.Th. Wenckebach, A.V. Muravjov, S.G. Pavlov and V.N. Shastin, The pulsed and mode locked p-Ge THz laser: wavelength dependent properties, EOS/SPIE International Symposia: Conference on Terahertz Spectroscopy & Applications, 16-18 June 1999, Munich, Germany. *SPIE* vol. 3828, pp..58 –67. 1999

[3] J. N. Hovenier, R. C. Strijbos, W. Th. Wenckebach, A. V. Muravjov, S. G. Pavlov and V. N. Shastin, “Active mode locking of a p-Ge hot hole laser”, *Appl. Phys. Lett*. vol. 71, pp. 443-445. July 1997.

[4] J. N. Hovenier, T. O. Klaassen and W. Th. Wenckebach, A V. Muravjov, S. G. Pavlov, and V. N. Shastin, “Gain of the mode locked p-Ge laser in the low field region”, *Appl. Phys. Lett*. vol. 72, pp. 1140-1142. March 1998.

[5] J. N. Hovenier, M. C. Diez, T. O. Klaassen, , W. Th. Wenckebach, A.V. Muravjov, S. G. Pavlov, and V. N. Shastin.”The p-Ge Terahertz laser: properties under pulsed and mode locked operation”, *IEEE Trans. on Microwave Theory and Techniques* vol. 48, pp. 670-676, 2000.