Time resolved TeraHertz Emission in Si:P under Resonant Pumping of Donor Centres with Picosecond Optical Pulses.

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Optical pumping of the 1s(A) → $2p_0$ transition in Si:P at cryogenic temperatures leads to stimulated THz emission on the $2p_0$ → 1s(E) transition at λ = 58.5µm (5.13 THz). Using the Dutch Free Electron Laser FELIX, the stimulated THz emission has been studied as a function of the power and time structure of the train of 6 ps FWHM pump pulses at λ = 36 µm. The occurrence of very short stimulated emission pulses are discussed in terms of optical gain, lifetime of the impurity states and the THz photon lifetime in the cavity.

Introduction

Semiconductors doped by shallow Coulomb impurities are promising materials for THz light amplification [1]. At low temperatures, life times of the impurity states are determined by intra- and inter-valley phonon assisted relaxation processes. The precise structure of the phonon spectrum in combination with the impurity level structure, can lead to a situation in which the life time of a certain state exceeds that of a state at lower energy. Such a condition is a prerequisite for the creation of a population inversion and possible stimulated emission. In Si:P this effect occurs for the $2p_0$ state, leading to stimulated THz emission on the $2p_0 \rightarrow 1s(E,T_2)$ transitions, under optical pumping at cryogenic temperatures (Fig.1) [2]. We have used the frequency tunable Dutch Free Electron Laser (FELIX) to selectively populate donor levels. In this way the processes leading to stimulated THz emission can be studied directly and in great detail In order to gain more insight into the dynamics of the stimulated emission in Si:P time resolved experiments have been performed.

The FELIX radiation consists of a 4-6µs long “macro-pulse” at a repetition rate of 5Hz. A macro-pulse consists of a train of micro-pulses, separated by either a 1 or a 40 ns time interval (see fig. 2). In this experiment, each micro-pulse had a ~6ps duration and a maximum peak power of about 0.5MW. The stimulated THz emission pulses from the Si crystals were detected with a Helium cooled, Ge:Ga, detector with a 1-2 ns rise time. The crystals were shaped into rectangular parallelepipeds (typical size of 7x5x5mm) with the facets polished parallel to each other, forming a mirror-less Fabry–Perot cavity. The Si:P sample had a doping concentration of about 3.10^{15} cm^{-3} and was uncompensated.

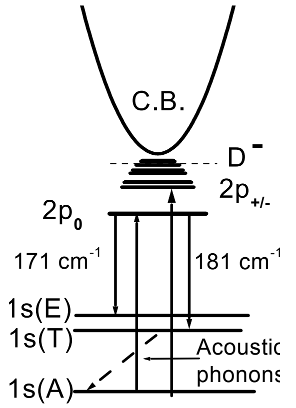

Fig. 1. Donor energy levels in Si:P

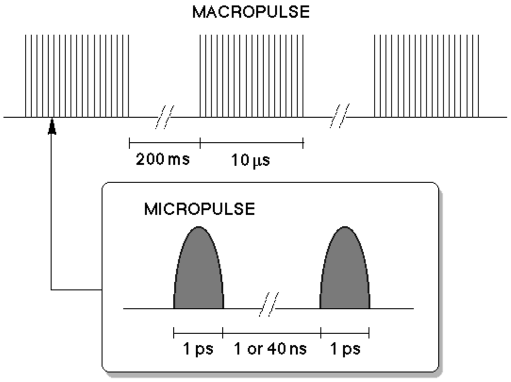

Fig. 2. Pulse structure of FELIX

Experimental results

Stimulated emission occurs on the $2p_0 \rightarrow 1s(E)$ transition at $\lambda = 58.5\mu m$, if the $2p_0$ state is optically populated by pumping the $1s(A) \rightarrow 2p_0$ transition at $\lambda = 36\mu m$. If the $2p_\pm$ or a higher excited state is optically populated, emission is observed on the $2p_0 \rightarrow 1s(T)$ transition ($\lambda = 55.6\mu m$) [3]. In fig. 3 the stimulated emission as a function of the FELIX pump energy is shown, together with the energy difference between ground- and excited donor states. In figure 4 the pulse shape of the $2p_0 \rightarrow 1s(E)$ stimulated emission as a function of pump power is shown. The full pump power (0 dB) is equivalent to a flux density of about 6.10^{14} photons/cm^2 per micro-pulse. The pump threshold for laser action is found to be at an attenuation of -24 dB. As the pump power is decreased, a clear increase of the time delay between the start of the FELIX pulse and the start of the stimulated emission is observed (up to 2.3 μs for –23 dB).

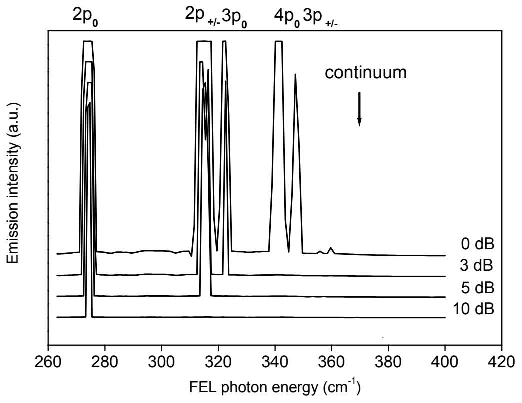

Fig. 3. Stimulated emission intensity as a function of FELIX pump energy and pump power attenuation

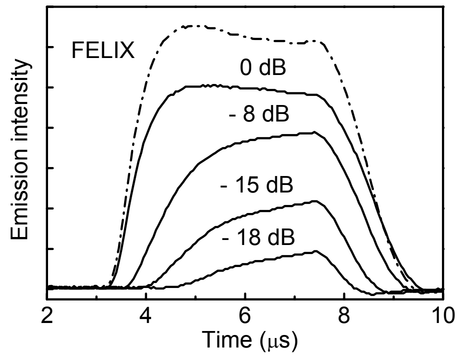

Fig.4. Shape of the FELIX pump pulse and the $2p_0 \rightarrow 1s(E)$ stimulated emission for various pump power attenuations.

Because this increase is also determined by the slow increase of the intensity of the leading edge of the FELIX pump pulse, no accurate information regarding gain can be obtained from these data. To circumvent the problem of the finite slope of the pump pulse, experiments were performed using an optical switch to extract a train of micro-pulses from the center of the FELIX macro-pulse. In figs. 5, 6 the FELIX pump pulse is shown to exhibit a rise time of about 1 ns. The intensity is about constant during the first

20 ns, followed by an exponential decay of the trailing edge with a time constant of the order of 30ns. The emission pulses at various pump attenuations show a rise time of the leading edge of about 1-2 ns. The limitations set by both the bandwidth of the Ge:Ga detector and/or the oscilloscope (0.5 GHz) together with the accuracy of the experimental data prohibit the determination of the small signal gain of the laser.

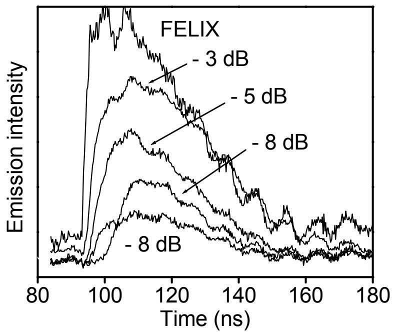

Fig.5 . Shape of the $2p_0 \rightarrow 1s(E)$ emission pulse under sliced FELIX pulse pumping of the $2p_0$ state as a function of pump power attenuation

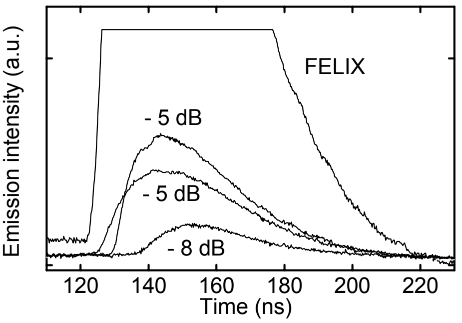

Fig. 6. Shape of the $2p_0 \rightarrow 1s(T)$ emission pulse under sliced FELIX pulse pumping of the $2p_\pm$ state as a function of pump power attenuation

As can be seen in figure 5 and 6 for – 8 and -5 dB pumping respectively, consistently either an emission pulse with short delay (1-2 ns) and a relatively low peak intensity, or a pulse with a 5 - 10ns delay and larger peak intensity is observed. For compensated Si:P crystals the emission pulses do not show this effect, but show the usual monotonous increase of the time delay and decrease of the peak intensity with increasing pump power attenuation. Preliminary analysis of the data suggests that in uncompensated material the long-living D^- centers might act as a reservoir for optically excited electrons, thereby opening a second channel for the build-up of population inversion and thus laser action.

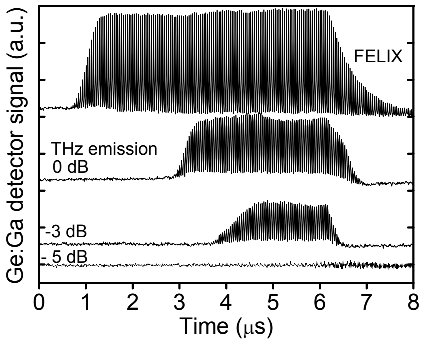

Fig.7. FELIX and THz pulse train under 40 ns micro-pulse interval pumping

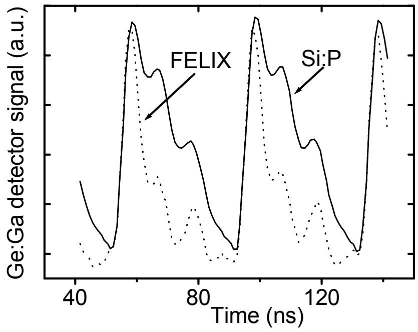

Fig. 8. Detailed view of FELIX and THz pulse shapes

To approximate single pulse excitation, a train of micro-pulses with a 40 ns time interval has been used. In figure7. a typical FELIX macro-pulse, together with the $2p_0 \rightarrow 1s(E)$ emission pulse, is shown. In both the pump and emission traces clearly separate pulses are visible. For an attenuation of the pump power greater than –3dB no THz emission is observed. In figure 8 a more detailed view of the micro-pulse shapes is given.

The combined response of the Ge:Ga detector and electronics to the 6ps FELIX pulses results in a steep leading edge (≈ 1ns) followed by a steep trailing edge with a long tail due to thermal processes in the detector. The periodic modulations are caused by reflections in the electronic circuit. The THz emission pulse signal exhibits a very steep rising edge together with similar modulations of the intensity in the falling edge. It is however evident that the THz pulse exhibits a more intense and longer tail than the FELIX pulse. That additional signal should therefore reflect the actual shape of the emission pulse. It can thus be concluded that in response to a very short pump pulse, Si:P emits a stimulated THz emission pulse characterised by a very short leading edge with a tail of a few tens of nanoseconds.

Discussion

The lifetime of (amongst others) the $2p_0$ state in Si:P has been measured recently using pump-probe experiments to be approximately 70 ps [4]. In view of this short lifetime it is clear that, under optical pumping, actual amplification of the THz field inside the crystal occurs for only ~0.1ns. The long tail therefore reflects the long cavity lifetime of the created photons, rather than the lifetime of the population inversion. Inspecting the shape of the emission pulse train in fig. 7, it is seen that there is a 1.9(2.6) μs time delay with respect to the FELIX pulse for 0 (-3)dB pump power attenuation. The micro-pulse intensity exhibits a gradual growth under a constant FELIX excitation power, with an exponential rise time of approximately 80 (180) ns. This clearly indicates the presence of an ongoing amplification process with a relatively small gain. Evidently, we are not dealing with a "single pulse" excitation after all. In fact the long lifetime of the photons in the cavity means that, at the arrival of a pump pulse, a finite photon density from the preceding pump pulse is still present in the cavity. That assumption is in line with the observation that the modulation depth of the emission micro-pulse train in the stationary situation is about 0.89 for 0 dB. In the stationary situation, the cavity losses can be deduced from the modulation depth of the signal to be $\alpha_{cav} = -0.054\ ns^{-1}$. Using the rise time of the emission pulse train we deduce an small signal gain averaged over 40 ns of $\alpha_{ssg} = 0.067\ ns^{-1}$. Because of the very short actual amplification time, that means a "step" amplification of the micro-pulse by a factor 15.

Acknowledgements

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