First Observation of a THz Photon Echo

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***Abstract*—We demonstrate THz photon echoes from silicon doped with phosphorus donors. We provide experimental evidence showing that the echo emerges at the predicted angle and that it arrives at our detector at the predicted time. We use this to demonstrate coherent control of the silicon donor states.**

I. Introduction and Background

In the last decade, there has been resurging interest in the physics of group-V donors in silicon. This has recently lead to a dramatic increase in activity in the research field. Much of this renewed interest stemmed from a proposal by Kane that silicon doped with group-V donors might be exploited to realise a quantum computer [1]. Many experiments have been recently performed to investigate the feasibility of this scheme. These include measurements of both the spin lifetimes [2] and lifetimes of the donor Rydberg states [3]. The second important development that rekindled interest in this research field was the invention of the optically pumped silicon laser [4]. This breakthrough was the first demonstration of lasing in a silicon-based material, and to-date lasing at THz frequencies has now been demonstrated for all four Group-V donors. Recent work also suggests the possibility of electrically pumped lasing in this material system [5]–[7].

In this paper, we will present convincing evidence for the first observation of a THz photon echo. The photon echo is a purely quantum mechanical effect and it has no classical interpretation. It is the optical analogue of the spin echo commonly observed in Nuclear Magnetic Resonance (NMR) or Electron Spin Resonance (ESR) experiments. Since the photon echo is a coherent quantum effect, we needed a coherent source of THz radiation. The experiments described were performed using the FELIX free electron laser at the FOM institute at Nieuwegein in the Netherlands. A full description of the experiment can be found in our recently published paper [8]. The main cogent points, however, are summarized in this conference abstract.

II. Theory

For typical donors in Si, the lowest energy Lyman series line is in the THz regime. In the case of phosphorus (P) the $1s(A_1)$ to $2p_0$ transition is at 34.2 meV, equivalent to 36.2 μm and 8.29 THz [9]. Previous frequency [10] and time-domain studies [3] have established the astonishing longevity of the excited states, with a population lifetime T_1 of 200 ps for the $2p_0$ state (due to 1-phonon emission augmented by intervalley and umklapp processes and corresponding oscillator quality factors of 2000 or more).

A two-level atom resonantly illuminated by the high intensity coherent light from a laser undergoes Rabi oscillations at a frequency given by $\Omega = F_0\mu_{12}/\hbar$ where F_0 is the electric field envelope of the light beam and μ_{12} is the transition dipole matrix element. For a pulse of finite duration, the excited state polarization that remains in the system after the pulse has passed varies sinusoidally with the pulse area, $A_P = \mu_{12}/\hbar \int F(t)dt$. If the laser is at resonance with the $1s(A_1)$ to $2p_0$ transition, it will produce a linear superposition of $1s(A_1)$ and $2p_0$ wavefunctions a very simple wavepacket which oscillates in time as the superposition precesses around the Bloch sphere, representing the quantum mechanical state space for two-level systems. For an ensemble, all the wavepackets initially radiate in phase, and therefore strongly, to produce coherent radiation. The coherence is lost, owing to small offsets in the resonant frequencies resulting from differences in the local environment, and the radiation weakens as the dipoles dephase on a timescale given by the inverse of the $1s(A_1)$ to $2p_0$ inhomogeneous linewidth. However, their relative phases can be restored by a subsequent laser pulse leading to a second burst of coherent radiation the photon echo which appears later by a time equal to the time difference between the initial and rephasing pulses, in precise analogy to the well-known Hahn spin echo.

III. Experimental Results

In order to provide conclusive proof of a true photon echo we need to establish both the directional property and expected timing of the phenomenon. This is now discussed.

We establish the directional property of the echo ($\boldsymbol{k_E} = \boldsymbol{2k_2} - \boldsymbol{k_1}$) by measuring the angular distribution of the beams. In our experiment the pump ($\boldsymbol{k_1}$) and rephasing ($\boldsymbol{k_2}$) beams intersect at an angle of -5^o. Simple geometry shows that the echo should emerge at an angle +5^o with respect to the direction of the rephasing beam $\boldsymbol{k_2}$. Figure 1 shows the intensities of the three beams exiting the sample as a function of angle. This graph shows that the echo emerges at the predicted angle with respect to the direction of the rephasing beam $\boldsymbol{k_2}$.

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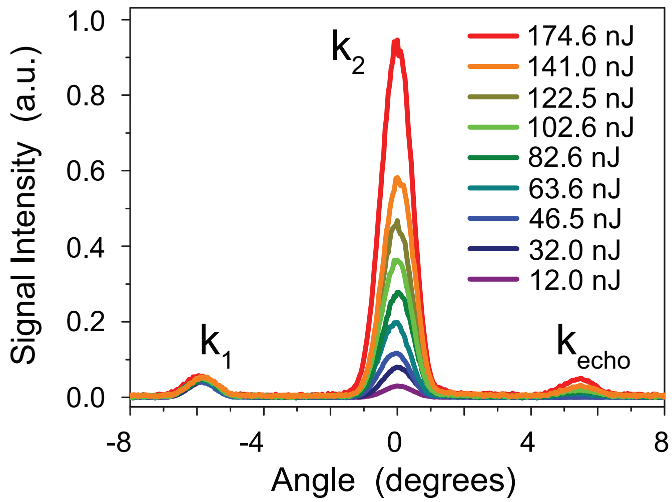

Fig. 1. Angle resolved echo. The intensities of the angle resolved signals were recorded by translating the detector across the far-field which shows that ($\boldsymbol{k_E} = \boldsymbol{2k_2} - \boldsymbol{k_1}$) as predicted.

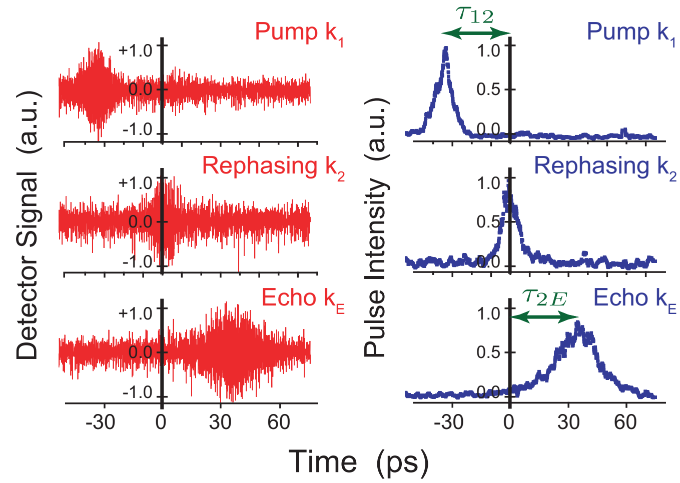

Fig. 2. Time resolved echo. On the left is the detector signal showing the interference patterns with the pump, rephasing and echo beams. A moving average has been subtracted, in order to remove the background and laser drift. The pump, rephasing and echo temporal profiles were obtained from the square of these interference patterns, as shown on the right, where the pump rephasing beam time interval τ_{12} and the rephasing beam-echo time interval τ_{2E} are also shown.

Second we consider the echo arrival time, which we determine using a reference pulse split from the rephasing pulse and a delay line. The transmitted pump, rephasing and emitted echo pulses, as well as the reference pulse are all focussed onto the detector through a pinhole to produce a characteristic interference pattern in time. We exploit the angular dispersion of the pump, rephasing and echo pulses and block all but one of them, thereby obtaining the interference patterns of the reference beam with the pump, rephasing and echo beams separately. By subtracting the mean intensity and squaring the result, the arrival times and shapes of the pump, rephasing and echo pulses can then be determined as a function of time (Figure 2). All three pulses take the form of well-defined peaks, with the maxima occurring at the times anticipated for echoes.

IV. Conclusion

We have provided the first demonstration a THz photon echo from phosphorus donors in silicon. We provide conclusive proof of this claim by establishing both the directional property and expected timing of the phenomenon.

We will go further in our conference presentation to show how we can use the experimental techniques we have developed to investigate coherent mixtures of different orbital states for phosphorus donors in silicon. Coherent control of donor orbitals in silicon opens up many possibilities such as entanglement of pairs of impurities whose ground state wavefunctions are too compact to interact. This could ultimately be exploited in a number of silicon-based quantum computing schemes that have been proposed in the literature.

Acknowledgment

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