Interactive Control of Photonic and Electronic Wave Packets

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1. Introduction

Opto-electronics has made tremendous impact to a wide range of technology including optical communication, information storage, precise measurement, and material processing. However, much wider areas of potential application are expected to come to realization, if we attain precise control and utilization of the optical phases, in addition to the frequency and amplitude. For example, the ultrashort optical pulses with several femtoseconds time duration are in the most advanced forefront of opto-electronics. Associated inevitably with the ultrashort duration is a large spectrum spread. If the phases of its frequency components are manipulated, recorded, and read-out at ultra-high speed consistent with the pulse duration, we expect to obtain extremely flexible high speed optical information handling scheme which combines the advantages of the frequency domain multiplexing and time domain multiplexing. In this project we aim at establishing a new device principle which will enable us ultrafast dynamic control of optical phases in femtosecond regime.

Optical pulses can be viewed as wave packets consisting of superposition of plane waves or cavity modes as

$$E(t) = \sum |E(\Omega_k)| \exp[i\Phi(\Omega_k)] \exp[ikr] \exp[-i\Omega_k t].$$

Technology is being developed to enable precise control over the phases of the constituent waves or modes. Irradiation with the optical wave packets can coherently excite superposition of the electronic wave functions, namely, an electronic wave packet, in the irradiated material. The wave packet can also be represented by the linear superposition of the eigenfunctions as

$$\Psi(r,t) = \sum |b_k| \exp[i\phi_k] \psi_k(r) \exp[-i\omega_k t].$$

By choosing material having appropriate energy level structure, we can imprint the phase information in the exciting optical pulse on those in the electronic wave packet. Furthermore, the phase information in an electronic wave packet may be manipulated and read-out by control and probe optical pulses. Figure 1 shows a schematic diagram of the new guiding principle named as "interactive control of the optical and electronic wave packets" or "wave packet engineering".

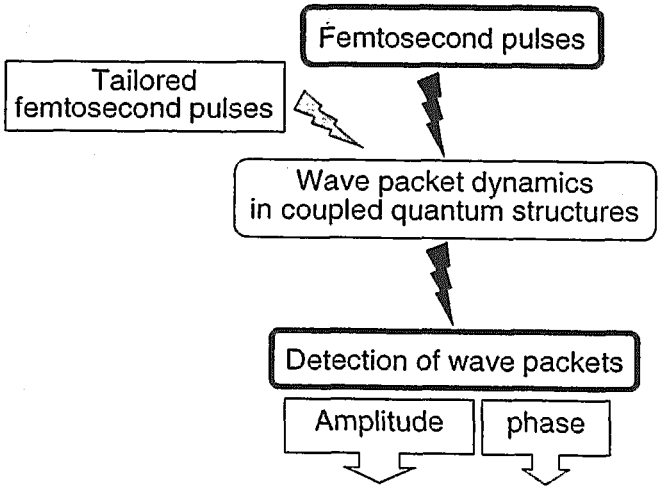

Fig. 1: Schematic diagram of "wave packet engineering"

In this project we explore the

possibility of precise control and utilization of the optical and electronic wave packet interaction using semiconductor nanostructure materials, such as quantum wells and quantum dots. The wave packet engineering is based on the following four subjects, 1) tailoring the shape and phase of femtosecond pulses, 2) theoretical study on temporal propagation of the wave packet, 3) generation and detection of the wave packet, and 4) design and fabrication of semiconductor nanostructures.

2. Tailored femtosecond pulses

The development of a phase programmable femtosecond optical source is the first step for generation and detectection of electronic wave packets in semiconductor nanostructures. We are developing all solid-state Ti:sapphire amplifier, which generates femtosecond pulses with arbitrary pulse profile and phase. The diagram of the total system is depicted in Fig. 2. Nearly transform-limited pulses from a Ti:sapphire seed laser is delivered into a programmable phase modulator. The output from the phase modulator is characterized, and the measured phase information is processed in a PC and fed back to the phase modulator for adjustment of the phase mask. A desired phase pattern can be realized through the iterative adjustment.

The phase modulated pulses are amplified in a Ti:sapphire amplifier. A LD-pumped Q-switched Nd:YLF laser is the excitation source of the amplifier, which greatly improve the stability of the amplified output. Amplification is necessary in order to obtain a high peak power for wavelength conversion to the near infrared in the range of 1~2μm, and optical nonlinear measurement. We investigated the performance of the phase modulator, amplifier, and pulse characterization instrument, individually. The combination of these components is in the progress.

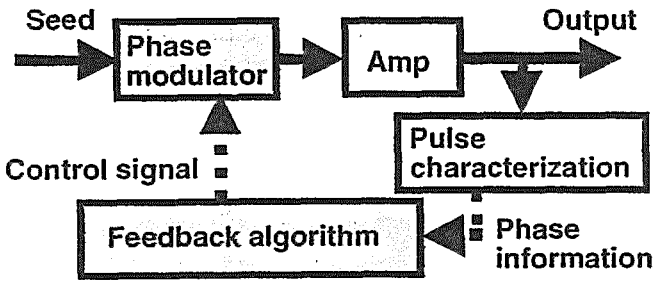

Fig. 2: Diagram of the phase-programmable femtosecond pulse source

3. Phase sensitive wave packet dynamics

We have already demonstrated phase-sensitive wave packet dynamics in organic dye molecules. Excited-state population in a cyanine molecule (DTTCI) is observed to be strongly dependent on the amount and sign of the chirp, when the dye molecule is excited by femtosecond chirped pulses. Figure 3 shows the time dependence of the transmittance change induced by excitation pulses with several chirp rates. The pulse energy, and spectrul profiles are equal to each other inall caes. Even the pulse duration is almost the same when the amount of chirp is equal but the direction of the chirp is opposite. In case of negatively-chirped pulses, the excited-state population is almost completely dumped just after excitation. On the contrary, a Large amount of population remains in the excited state for positively chirped-pulses. This phenomena can be explained in terms of the pump-dump process, where the excited-stated wave packet generated by the leading edge of the excitation pulses is driven back to the ground state through the stimulated emission induced by the trailing edge of the pulses.

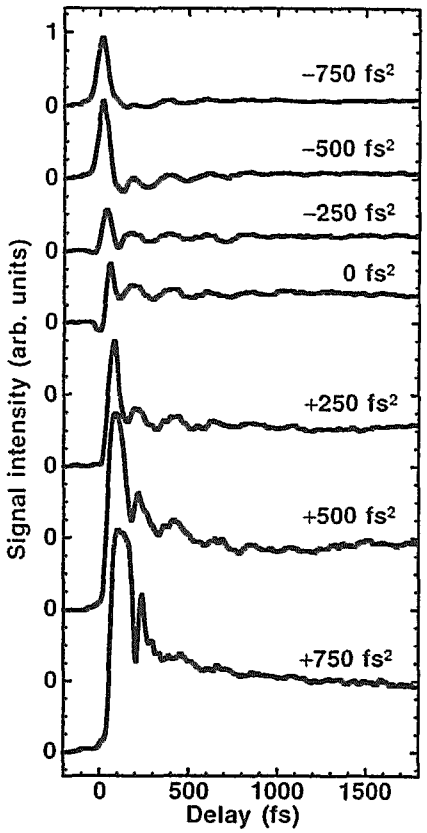

Fig. 3: Time dependence of the transmittance change induced by excitation pulses with several chirp rates

We have performed a quantum mechanical calculation for an electronic two-level system coupled to a single vibrational mode, and successfully reproduced the experimental observation. The result is consistentwith the experimental result.In case of negatively chirped excitation, the spatial distribution of the excited wave packet is narrow, because pulse chirp compensates the dispersion among the frequency components of the wave packet. The overlap integral between the excited- and ground-state wave packets is large, and therefore the stimulated emission is efficiently induced. The difference in the spatial distribution of the excited-state wave packet can be seen at 0 fs between the negative and positive chirp cases.

The wave packet excited by positively chirped pulses is easily broadened and quickly escapes from the Franck-Condon window because of the dispersion in the excited-state potential surface. Absorption is dominant over the entire excitation process.

This result demonstrates a possibility to convert phase information into amplitude information. The negative and positive chirps correspond to the 0 (without amplitude change of transmitted light) and 1 (with amplitude change) codes, respectively.

4. Semiconductor nanostructures

The above mensioned experiment to control the wave packet dynamics by the pulse phase will be applied to the semiconductor nanostructures. The materials are selected because the energy level structures can be precisely designed and fabricated with the advanced semiconductor growth and fabrication technology. The electronic wave packet is constituted by eigenstates of the material with corresponding amplitude $|b_k|$ and phase ϕ_k. Tailoring the amplitude and phase of the optical pulses for excitation results in the control $|b_k|$ and ϕ_k through the interaction between light and matters. Because the molecular eigenstates have complicated form due to the level crossing, it is difficult but challenging to optimize the amplitude and phase for desired wave packets using tailored femtosecond pulses. On the other hand, the main advantage of the quantum nanostructures is designability of the level structure. We propose to design the eigenfunctions $\psi_k(r)$ themselves as well as the amplitude and phase. For the wave packet engineering, the system needs to consist of N eigenstates and all N states must be accessible from a single initial state. The nanostructure, which satisfies these conditions, is an asymmetric coupled quantum wells or dots. One example is depicted in Fig. 4.

In semiconductor physics, mechanism of population relaxation and dephasing is one of the most important problems. Above all, the coherent propagation of the wave packets is limited by these relaxation mechanism in semiconductor nanostructures both theoretically and experimentally. Especially, long decay time due to phonon bottleneck is expected in quantum dots, but dephasing time as short as 200 fs is observed experimentally, which is of the same order as in bulk. We explaind such fast dephasing in quantum dots in terms of second-order elastic interaction with LO phonons.

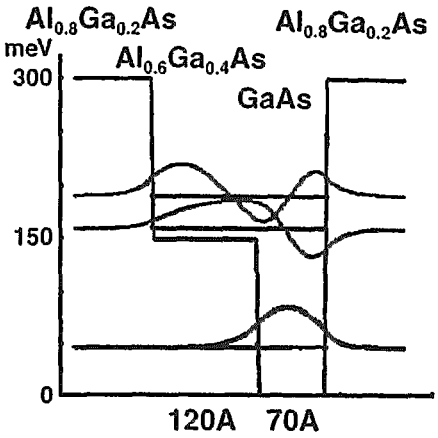

Fig. 4: Asymmetric coupled quantum well.

	Molecules	Semiconductors
Wave packet formation	Vibrational levels	Sublevels, fine structures
Dephasing time	100 fs ~ 1 ps	100 fs ~ 10 ps
Repetition rate	MHz	GHz
Round trip time	100 fs ~ 1 ps	10 fs ~ 100 ps
Potential designablity	poor	flexible
Optical durability	low	high

Table 1: Comparison between molecular systems and semiconductor nanostructures in terms of wave packet engineering.

We consider semiconductor naonstructures as one of the promising materials to realize wave packet engineering, because the material parameters are widely controllable. Table 1 compares several physical properties between molecular systems and semiconductor nanostructures.

5. Research plans

The project activity this year is concentrated on the following three areas. 1) Generation and control of femtosecond pulses in the wave length ranging from 1.1 μm to 1.5 μm, 2) design and fabrication of semiconductor nanostructure, and 3) theoretical study of the interaction between ultra-short optical pulses and electronic states in semiconductor nanostructures. Activity in the area 1) and 3) are mainly performed in Tokyo University of Agriculture and Technology, while that in are 2) is primarily carried out by our industrial partners. With very tight coordination of research activities in the three areas we explore the possibility of new concept of devices and systems based on optical phase control.

References

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