Interactive Control of Photonic and Electronic Wave Packets
----Project Overview----

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1.Introduction

Photonics technology has been making remarkable progress in past decades. Development of optical sources with the frequencies precisely controllable and tunable has made feasible the frequency domain division multiplexing (FDM) optical fiber transmission systems. Development of ultrafast optical pulse sources has enabled high capacity time division multiplexing (TDM) photonic systems.

Ultrashort optical pulses with several femtoseconds time duration are in the most advanced forefront of opto-electronics. Associated inevitably with the ultra-short temporal duration is a large spread in frequency. 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 that combines the advantages of the FDM and TDM schemes. In this project we aim at establishing a new device principles that will enable us ultrafast dynamic control and detection of optical phases in femtosecond regime through interaction of optical pulses with materials.

The basic idea is briefly summarized in the following. Femtosecond pulses can be expressed as a superposition of coherent plane waves, or an optical *wave packet*, as

$$E(t) = \sum |E(\Omega_k)| \exp[i\Phi(\Omega_k)] \exp[ikr] \exp[-i\Omega_k t] \qquad (1)$$

where, Ω_k, and $|E(\Omega_k)|$, $\Phi(\Omega_k)$ are the frequency, amplitude, and phase of the component waves. For femtosecond pulse of, say, 100 fs duration at the peak wave length of 800nm, the frequencies spread 10 meV. We may impose information on the pulse by controlling the phases $\Phi(\Omega_k)$, with some cost in temporal expansion of the pulse. Irradiation of suitable material system with the optical pulse will excite superposition of quantum states, that is, quantum wave packet, as

$$\Psi(r,t) = \sum |b_k| \exp[i\phi_k] \psi_k(r) \exp[-i\omega_k t] \qquad (2)$$

Here, $\Psi_k(r)$ and ω_k represents the wave function and energy in units of $\hbar$ of a constituent state. It can be the envelope part of full Bloch function in case of semiconductor nano-structures, and the nuclear wave function in case of excitation of molecular vibrational or rotational states.

Our goals are to understand the physical mechanism and develop technology to precisely control the phase, impose the phase information to the excited materials wave packet, and optically manipulate and read out, all with optical pulses in femtosecond regime.

2. Project organization

Research activities at present focus primarily on the following topics

(1) Development of phase programmable fs optical sources

The development is in progress of fs laser pulse sources in which arbitrary combination of phase information can be imposed on the individual plane wave component.

(2) fs phase spectroscopy

Spectroscopic technique based on a unique pulsed Sagnac interferometry is being developed to detect the temporal changes in the complex dielectric constant induced in material samples, which bears the evidence of quantum wave packet generation. Development of cross-correlation frequency resolved optical gating (XFROG) is also in progress.

(3) Coherent control of quantum wave packets

Manipulation and readout of generated quantum wave packets are being investigated with pump and control double multi-pulse technique.

(4) Analysis, design, and fabrication of semiconductor nanostructures

Semiconductor nanostructures such as quantum dots (QDs) and quantum wells are expected to be suitable for quantum wave packet generation, because of the designability of the energy levels and wave functions.

Acitivities for items (1) and (2) are carried out primarily at Tokyo University of Agriculture and Technology (TUAT), (3) at Tohoku University, and (4) at TUAT, NEC Corporation, and the Femtosecond Technology Research Association (FESTA).

3. Recent Results

In the following some of the recent accomplishments are briefly described, with the details left in separate accompanying reports.

3.1 Development of a phase-programmable femtosecond optical source

A phase-programmable femtosecond optical source has been developed [1], which is capable of imposing arbitrary phase shift independently to individual frequency components. It consists of a Ti:sapphire seed laser, a programmable phase modulator, and a frequency resolved phase analyzer whose output is fed back to the modulator in order to attain the preprogrammed phase shift. The phase modulator is composed of a pair of grating and spherical mirror, and liquid crystal spatial light modulator (LC-SLM). Internal phase control has been demonstrated for femtosecond pulses with a spectral bandwidth as broad as 100 nm. With careful alignment, pure internal phase shift with very little angular dispersion has been attained.

Using positively- and negatively chirped pulses from this phase-programmable femtosecond optical source, chirp dependent quantum wave-packet generation has been demonstrated in a cyanine dye molecule (IR-140). The luminescence efficiency depends markedly on the chirp direction, which can be explained in terms of intra-pulse pump-dump process [2].

3.2 Femtosecond phase spectroscopy for wave packet detection

A promising method for detection of generated quantum wave packets is measurement of temporal variation of the real and imaginary part of nonlinear optical susceptibility. We have developed an original measurement scheme using Sagnac interferometer (SI) configuration, which enables us simultaneous measurement of both the real and imaginary parts. By measuring both of the components we can avoid relying on the Kramers-Kronig relationship which is known to present accuracy limitations in practical measurements with limited spectral range. An important advantage of the SI configuration is the stability. This single path configuration significantly improves the mechanical and thermal stability of interferometers, in contrast to two arm interferometers. The original version of the SI based femtosecond interferometer scheme was reported earlier [3]. In the present version [4] improvement in the detection sensitivity has been attained, by replacing the CCD detector with a photodiode having pinhole mask to scan a small portion of the interference fringe obtained from SI.

An alternative scheme based on cross-correlation- Frequency Resolved Optical Grating (XFROG) has also been developed [5]. These apparatus will be very useful also for evaluation of materials for ultrafast optical devices.

3.3 Coherent control of quantum wave packets

A very significant possibility in wave packet engineering is coherent control of quantum wave packets, that is, control of a quantum wave packet generated in material with subsequent coherent optical pulses. The applicability is expected to go far beyond just the manipulation and readout of quantum wave packets. It is expected to open up new possibilities such as coherent control of chemical and biochemical reaction processes, quantum information and transportation engineering, and quantum computing. We have successfully demonstrated coherent control of vibrational wave packets at attosecond precision using Hg-Ar van der Waals (vdW) complex generated in a supersonic jet.[6-9] Two identical fs laser pulses (254nm, 300fs), one delayed with respect to the other are used to create and control the wave packets consisting of coherently superposed vibrational eigenfunctions (v = 3, 4, and 5 levels) of the excited A state of the molecule. The inter-pulse-delay is tuned with accuracy better than 5 attoseconds. With this double-pulse pump-control method, almost 100% contrast, depending on constrictive and destructive interference between the wave packets created by the pump and the control pulses, has been attained for the first time in wave packet interferometry.

3.4 Effects of carrier relaxation processes on quantum dot laser properties

In semiconductor nanostructures, such as quantum wells and quantum dots (QDs not only the energy levels but also the form of wave functions can be designed at will, by suitable combination of materials, size, and shape of those structures. Research is in progress to seek design principles for nanostructures to sustain quantum wave packets, and fabrication technology for better size controlled quantum dots.

Also important in designing these structures are the phase and energy relaxation processes for carriers. On one hand, the relaxation cause dephasing among quantum states and destroy quantum wave packets. On the other hand, relaxations at appropriate rates are essential in attaining high quality device performance, for example of QD lasers.

Theoretical studies have been carried out on the energy relaxation rates among confined levels, and between continuum and confined levels in quantum dots[10-11]. Analysis of hole-burnings that lead to multi-mode lasing in QD lasers have revealed that the extent of spectral and spatial hole-burning depends critically on the energy relaxation rate between the continuum in the confining (or wetting) layer and the discrete confined levels, and on the spatial carrier diffusion in the confining layers [12]. Much attention is now being focused to the dynamic response properties of QD lasers to current modulation. Very sensitive dependence of dynamic response characteristics to inter sub-level relaxation rates and the Pauli blocking in the lasing confined levels have been found, as described more in detail as a separate report in this proceedings.

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