A Novel Method of All-Optical Switching: Quantum Router

Byoung Seung Ham

Subpicosecond all-optical switching method based on the simultaneous two-photon coherence exchange is proposed and numerically demonstrated. The optical switching mechanism is based on the optical field induced dark resonance swapping via nondegenerate four-wave mixing processes. For potential applications of ultrafast all-optical switching in fiber-optic communications, 10-THz channel number independent quantum router is discussed.

I. INTRODUCTION

Since the observation of non-absorption resonance [1], many researchers have studied basic physics of dark resonance phenomenon by using atomic gases [2], [3], impurity ion doped crystals [4], and semiconductor quantum wells [5], [6]. Owing to bigger oscillator strengths and sharp absorption lines in dipole transition media, atomic gases have been studied intensively for the dark resonance and its potential applications to nonlinear optical processes. Atomic gases, however, have fundamental drawbacks such as atomic diffusion that limits applications of, for example, optical memory and image processing. Therefore, suitable solid media have been sought for the potential applications of the dark resonance. Recent observation [7] of nonlinear optical processes based on the dark resonance in rare-earth doped solids opens the door to practical applications of optical memories [8], enhanced nonlinear optical processes [9], lasers without inversion [10], and optical switches [11], [12]. In this paper, a novel phenomenon of the optical switching is discussed for channel number independent ultrafast optical switches in fiber optic communications.

In a three-level system composing two closely spaced ground states and a common excited state, two resonant optical fields can excite a strong coherence on the ground states via two-photon resonance. This strong coherence is dependent on a superposition state created by the atom-field interactions, which is decoupled from the excited state, so that an optically thick medium can be transparent to the resonant optical field [1]-[6]. This decoupled state is the origin of the dark resonance causing the two-photon coherence. Based on the dark resonance, ultrahigh conversion efficiency in four-wave mixing processes has been demonstrated in atomic vapors [13] and impurity-ion doped crystals [14]. Not only high conversion efficiency but also large

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Byoung Seung Ham (phone: +82 42 860 1309, e-mail: bham@etri.re.kr) is with the Telecommunication Basic Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, Korea.

signal amplification was demonstrated in atomic vapors [15]. Another feature of the dark resonance is spectral narrowing so that the two-photon coherence or four-wave mixing generation does not experience any spectral dispersion.

In a four-level system, however, the dark resonance can interact with each other constructively or destructively. When three resonant laser fields (ω_1, ω_2, and ω_3; no ω_p this time) are applied to the four-level system in Fig. 1 (δ=0), one of the coherences created on the transitions of the three-ground states can be suppressed while the others are enhanced [11]. In Fig. 1(a) coherent phase gratings can be formed by noncopropagating laser fields ω_1 & ω_3 and ω_2 & ω_3 under dark resonance conditions on the transitions |a>-|c> and |b>-|c>, respectively. The phase grating is then detected by nondegenerate four-wave mixing processes satisfying the Bragg conditions. Very recently the coherence switching, so-called quantum switching, was experimentally demonstrated in a continuous wave scheme by using a rare-earth doped crystal [11]. The quantum switching is very useful to ultrafast optical switches because the switching time can be as fast as the Rabi frequency even in slow relaxation systems [16].

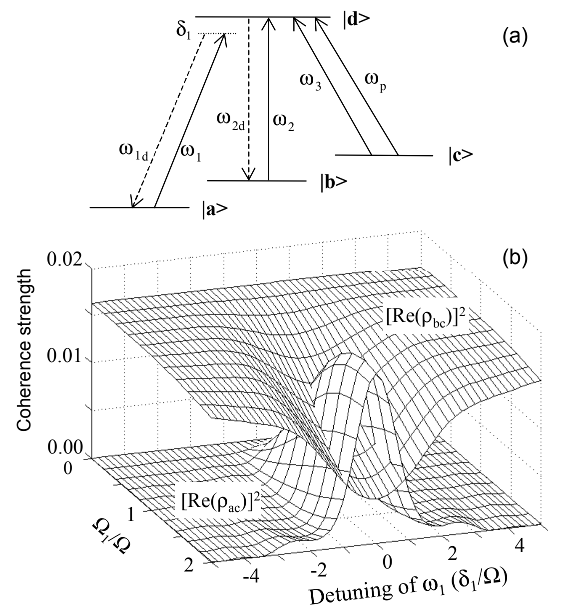

Fig. 1. (a) Energy-level diagram and (b) numerical calculations of coherence swapping as functions of detuning and Rabi frequency of ω_1; Γ_{da}= Γ_{db}=Γ_{dc}=1.5 THz, γ_{da}=γ_{db}=γ_{dc}=2 THz, γ_{ab}=γ_{bc}=γ_{ac}=1.5 THz, Ω_2=Ω_3=Ω=4 THz, and the laser interaction time = 0.1 ps.

Semiconductor quantum-wells or dipole-transition-allowed solids can be good candidates for the implementation of the quantum switches. In the semiconductor quantum-wells, the matrix element for the intersubband transitions is much larger than that for the interband transitions [17]. Recently quantum-well intersubband transitions at communication wavelength (1.3/1.55 μm) were observed [18]. As introduced already, dark resonance in multiple-quantum-wells was demonstrated by using moderate laser power exceeding THz Rabi frequency [5]. Therefore, implementation of the quantum switching in semiconductor quantum wells utilizing the intersubband transitions is very plausible for the applications of hyper-THz optical switching in fiber optic communications.

II. THEORY

For theoretical studies of the quantum switch, a homogeneously broadened optical system is considered. In Fig. 1(a), the interaction Hamiltonian matrix is

$$H = -\frac{\hbar}{2}\begin{bmatrix} -2\delta_1 & & & \Omega_1 \\ & -2\delta_2 & & \Omega_2 \\ & & -2\delta_3 & \Omega_3 \\ \Omega_1 & \Omega_2 & \Omega_3 & 0 \end{bmatrix}, \tag{1}$$

where δ_1=ω_1–ω_{ad}, δ_2=ω_2–ω_{bd}, and δ_3=ω_3–ω_{cd}. Ω_i (i = 1, 2, 3) is the Rabi frequency of the laser field E_i(r, t) for ω_i:

$$E_i(r, t) = 1/2\varepsilon_i(t)\exp\{i(\omega_i t\text{-}k\cdot r)\}+\text{c.c.}, \tag{2}$$

$$\Omega_i = 2\pi\mu\varepsilon_i(t)/h \tag{3}$$

where c.c. and h are complex conjugate and Planck constant, respectively, and $\varepsilon_i(t)$ is amplitude of an applied electric field E_i(r, t). To describe the system's probability of ensemble, density matrix operator ρ is introduced to the state vector | Ψ >:

$$\rho = |\Psi><\Psi| \tag{4}$$

where $$|\Psi> = \sum_i a_i(t)\exp(-i\varepsilon_i t/\hbar)\,|\,u_i>.$$

The equation of motion of the density matrix is obtained from the Shrödinger equation:

$$|\dot{\Psi}> = -\frac{i}{\hbar}H\,|\Psi>. \tag{5}$$

Taking the time derivative of ρ, Liouville equation is obtained:

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + (\text{decay terms}). \tag{6}$$

According to (6),

$$\dot{\rho}_{ij} = -\frac{i}{\hbar}\sum_{k}(H_{ik}\,\rho_{kj} - \rho_{ik}\,H_{kj}) - \frac{1}{2}(\gamma_{ik}\,\rho_{kj} + \rho_{ik}\,\gamma_{kj}). \quad (7)$$

From (1) and (7), total 16 density matrix equations are obtained. The time-dependent density-matrix equation of motion in the matrix form is

$$[\dot{\rho}]_{ij} = [M]_{ik}[\rho]_{kj}, \quad (8)$$

where the matrix M is the interaction Hamiltonian and is shown in (9).

III. RESULTS

For numerical calculations of the quantum switch, a closed four-level system is considered, *i.e.*, $\rho_{aa}+\rho_{bb}+\rho_{cc}+\rho_{dd}=1$. In Fig. 1(b), the coherences $\mathrm{Re}(\rho_{ac})$ and $\mathrm{Re}(\rho_{bc})$ are calculated as functions of detuning δ_1 and Ω_1 for 0.1 ps interaction time; sub-ps is a typical quantum-well intersubband relaxation time [5], [6], [17], [18]. As shown in Fig. 1(b), the coherence strength $[\mathrm{Re}(\rho_{ac})]^2$ and $[\mathrm{Re}(\rho_{bc})]^2$ are swapped with each other at line center of the ω_1 when Ω_1 is larger than Ω. Here, the four-wave mixing signal intensity $I_{2d}(\omega_{2d})$ is proportional to both the probe signal intensity (if no saturation happens) and the coherence strength [14].

To demonstrate quantum switching in time domain the 16 density matrix equations are numerically calculated for a series of input pulses. In Fig. 2, the input signals stand for ASCII let-ter "E" in a non-return-to-zero binary code format. For the numerical calculations, a homogeneously broadened optical system is assumed. Two optical pulses temporally and spatially overlap in the medium, and the position (along the propagation direction) dependent nonlinear effect is neglected. The shape of the optical pulses is simply assumed to be square. To satisfy the condition of the two-photon coherence swapping in Fig. 1, Rabi frequency Ω_2 of the optical field ω_1 is set to be twice bigger than the Ω_1. Figure 2(a) shows that the coherence $\mathrm{Re}(\rho_{bc})$ is much bigger than $\mathrm{Re}(\rho_{ac})$ when $\delta_1 \neq 0$. On the contrary, each coherence strength is reversed at $\delta_1=0$ in Fig. 2(b). Thus, the fast modulated (10 THz) input signals are switched according to the value of δ_1 with high contrast ratio. As seen in Fig. 2, the switching time is 0.1 ps and the switching repetition rate (10 THz) is much

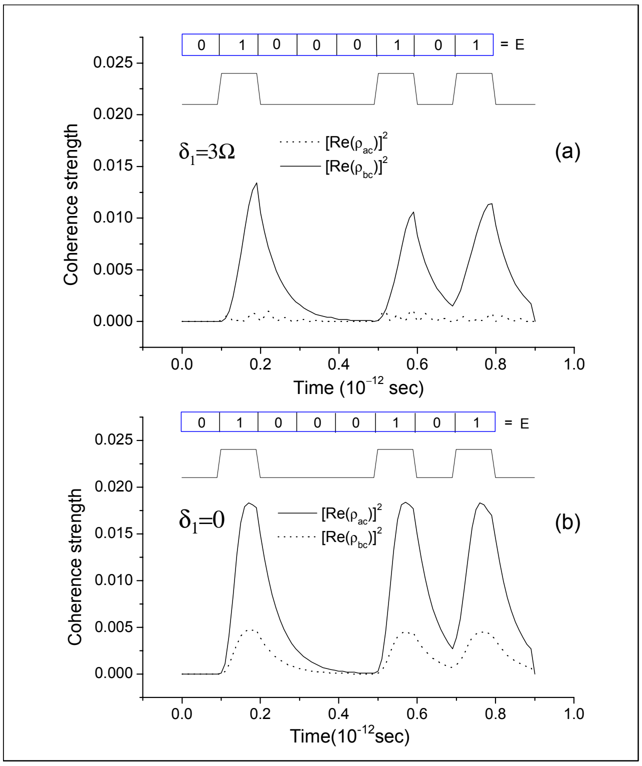

Fig. 2. Numerical calculations of coherence switching for (a) $\delta_1=3\Omega$ and (b) $\delta_1=0$; $\Gamma_{da}=\Gamma_{db}=\Gamma_{dc}=1.5$ THz, $\gamma_{da}=\gamma_{db}=\gamma_{dc}=2$ THz, $\gamma_{ab}=\gamma_{bc}=\gamma_{ac}=1.5$ THz, $\Omega_2=\Omega_3=4$ THz, and $\Omega_1=8$ THz.

$$\frac{\partial}{\partial t}[\boldsymbol{\rho}]_{ij} = \begin{bmatrix}
 & & & \Gamma_{41} & & & & & -i\Omega_1 & i\Omega_1 & & & & & & \\
 & & & \Gamma_{42} & & & & & & & & & -i\Omega_2 & i\Omega_2 & & \\
 & & & \Gamma_{43} & & & & & & & & & & & -i\Omega_3 & i\Omega_3 \\
 & & & -(\Gamma_{42}+\Gamma_{42}+\Gamma_{43}) & & & & & i\Omega_1 & -i\Omega_1 & & & i\Omega_2 & -i\Omega_2 & i\Omega_3 & -i\Omega_3 \\
 & & & & -i\Delta_1-\gamma_{12} & & & & -i\Omega_2 & & & & & i\Omega_1 & & \\
 & & & & & i\Delta_1-\gamma_{21} & & & & i\Omega_2 & & & -i\Omega_1 & & & \\
 & & & & & & -i\Delta_1-\gamma_{13} & & -i\Omega_3 & & & & & & & i\Omega_1 \\
 & & & & & & & i\Delta_1-\gamma_{31} & & i\Omega_3 & & & & & -i\Omega_1 & \\
-i\Omega_1 & & & i\Omega_1 & -i\Omega_2 & & -i\Omega_3 & & -i\Delta_1-\gamma_{14} & & & & & & & \\
 & & & -i\Omega_1 & & i\Omega_2 & & i\Omega_3 & & i\Delta_1-\gamma_{41} & & & & & & \\
 & & & & & & & & & & -\gamma_{23} & & -i\Omega_3 & & & \\
 & & & & & & & & & & & -\gamma_{32} & & i\Omega_3 & & \\
 & -i\Omega_2 & & i\Omega_2 & & -i\Omega_1 & & & & & -i\Omega_3 & & -\gamma_{24} & & & i\Omega_2 \\
 & i\Omega_2 & & -i\Omega_2 & i\Omega_1 & & & & & & & i\Omega_3 & & -\gamma_{42} & -i\Omega_2 & \\
 & & -i\Omega_3 & i\Omega_3 & & & & -i\Omega_1 & & & & -i\Omega_3 & & & -\gamma_{34} & \\
 & & i\Omega_3 & -i\Omega_3 & & & i\Omega_1 & & & & i\Omega_2 & & & & & -\gamma_{43}
\end{bmatrix}[\boldsymbol{\rho}]_{ij} \quad (9)$$

wider than the population relaxation decay rate (4 THz) of the optical medium, which is a fundamental limitation of the current semiconductor optical switching technologies [19].

For the potential applications of the quantum switching to the fiber-optic communications, 1× 2 all-optical router is considered. Compared with the conventional optical switches such as MEMS, whose switching speed is channel-number-independent but slow, and Mach-Zehnder type switch, whose switching speed exponentially slowes down as the channel number increases, the present quantum switch implies not only channel number independent ultrafast processing but also signal amplification with even noise quenching based on the dark resonance characteristics. The channel number independence is due to the phase dependent coherence overlapping; this coherence superposition is a general principle of holographic memories [20]. The signal amplification is owing to the energy transfer from the pumping fields to the input signal [13], [15]. The noise quenching is by the spontaneous emission squeezing owing to the atomic coherence [21] and quantum interference [22].

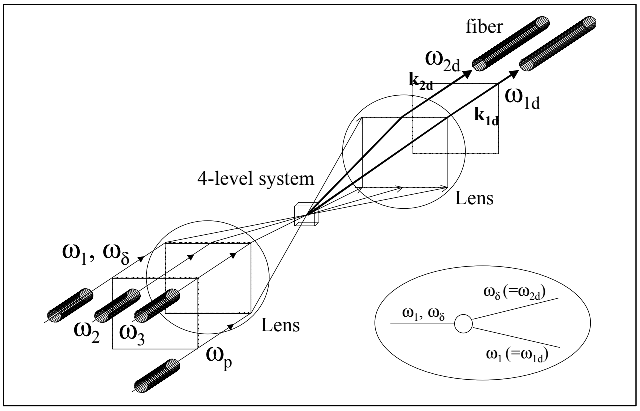

Fig. 3. A schematic of all-optical switch: quantum router.

Figure 3 shows a schematic of a 1× 2 all-optical switch: a quantum router. Let's consider two groups of input signals ω_1 (δ_1=0) and ω_δ ($\delta_1 \neq 0$) (see the inset) for DMUX. According to the coherence swapping in Fig. 1, the input signals are routed into the directions of $\mathbf{k_{1d}}$ for the input ω_1 and $\mathbf{k_{2d}}$ for the input ω_δ, respectively. This optical routing mechanism is based on the two-photon coherence grating formed by a set of two non-copropagating optical fields as mentioned above. The $\mathbf{k_{1d}}$ ($\mathbf{k_{2d}}$) produced by the nondegenerate four-wave mixing processes satisfies the Bragg conditions between $\mathbf{k_p}$ and the coherence grating formed by $\mathbf{k_3}$ and $\mathbf{k_1}$ ($\mathbf{k_2}$) [7]. If wavelength conversion is not necessary, the frequency difference between ω_1 and ω_δ must satisfy $\delta_1=2\pi\varepsilon_{ba}/h$, where $\varepsilon_{ba}=\varepsilon_b-\varepsilon_a$ and ε_i is energy of |i>. For a 1× 2 all-optical router, δ_1 of the ω_1 should act as a controller to route the ω_2 into either $\mathbf{k_{1d}}$ or $\mathbf{k_{2d}}$. Moreover, the 1× 2 optical switching mechanism can also be applied to wavelength converter, demultiplexer, and add/drop optical devices.

IV. SUMMARY

In summary, quantum switching in a four-level system using dark-resonance swapping was proposed and numerically demonstrated for a 0.1 ps in switching time and 10-THz in repetition rate. To implement the quantum switching, 1× 2 all-optical quantum router is suggested. The significance of the proposed quantum switching is given by the channel number independent ultrafast all-optical switching with signal amplification and line narrowing.

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Byoung Seung Ham received the B.S. from Sogang University, Seoul, Korea in 1986 and the M.S. and the Ph.D. from Wayne State University, Detroit, MI, USA in 1993 and 1995, respectively. From January 1996 through July 1999, he worked as a postdoctoral associate with MIT, Cambridge, MA, USA, and as a research contractor with the US Air Force Research Laboratory, Hanscom Air Force Base, MA, USA. In July 1999, he joined ETRI, Daejeon, Korea as a senior researcher. In October 2000, he became a director of the Center for Quantum Coherence and Ultrafast Information Com-munications designated by Korean Ministry of Science and Technology through Creative Research Initiative Program. His research area is laser physics, quantum optics, and nonlinear optics. His research interest is in quantum information processing such as quantum switching, quantum computing, and quantum communications.