Ultrafast all-optical NOR gate based on intersubband and interband modulation operating at communication wavelengths

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Abstract: An ultrafast all-optical NOR gate using intersubband and interband transitions in quantum wells is proposed. A proof-of-principle experiment is demonstrated using InGaAs/AlAsSb coupled quantum well structures operating at communication wavelengths (1.55 µm and 1.3 µm).

OCIS codes: (320.7160) Ultrafast technology; (070.4340) Nonlinear optical signal processing; (320.7080) Ultrafast devices

1. Introduction

Signal processing using ultrafast optical time-domain devices offers significant advantages to accommodate the massive amount of traffic in terabit optical networks [1]. To perform this signal processing digitally requires a complete set of complementary logical operations, and the NOR operation forms one such set. Moreover, performance monitoring, such as error detection, is possible with NOR gates [2]. All-optical NOR gates using, for instance, optical fibers [3] or semiconductor optical amplifiers (SOAs) [4] have been successfully demonstrated. However, these have disadvantages, namely, large latency due to small nonlinearity in the case of silica fibers or low operation speed due to the large carrier life-time in the case of conventional SOAs.

2. Intersubband and interband transitions for all-optical logical operations

The intersubband transition (ISB-T) in semiconductor quantum wells, which occur within the conduction band, is one possible mechanism enabling all-optical logic; this mechanism has some attractive features, such as ultrafast relaxation, large transition dipole moment, and widely tunable transition wavelength [5]. Also, it has been known that ISB-T can be used simultaneously with the interband transition (IB-T) [6]. For example, when the electrons provided by n-type doping in a lower conduction subband are excited to an upper subband by ISB-T resonant light, the electron density temporarily decreases, and so the IB absorption increases. Therefore, the IB-T resonant light can be modulated by the ISB-T resonant light.

Here we propose applying ISB-T and IB-T to computation applications. An optical NOT gate is made possible by assigning an input signal to the ISB-T resonant light while synchronously irradiating the IB-T resonant light. The output signal is the modulated IB-T resonant light. When the input signal exists, the incident IB-T resonant light is absorbed and so the output signal does not appear. When there is no input ISB-T resonant light, the device is transparent for the IB-T resonant light and so the output signal is at the high level. Therefore, the NOT truth table shown in Fig. 1(b) is fulfilled.

Moreover, a NOR operation can also be implemented by the simple configuration shown in Fig. 1(c), where the two input signals (Input A and Input B) are first merged incoherently, and then act as ISB-T resonant light to the device. IB-T resonant light is also synchronously irradiated. If the optical power of inputs A and B is either 0 or P_{in}, the incident power to the device can be 0, P_{in}, or $2\times P_{in}$. The output signal, which is the modulated IB-T resonant light, should be at the low level when the incident optical power is both P_{in} and $2\times P_{in}$, thus achieving a NOR gate. This is accomplished by appropriately setting the signal level, since ISB-T causes absorption saturation. Therefore, the NOR truth table in Fig. 1(b) is also achievable.

3. Experiment using InGaAs/AlAsSb coupled double quantum well

Another important aspect is the operation at telecommunication wavelengths (1.3 µm and 1.55 µm), which is made possible by an InGaAs/AlAsSb coupled double quantum well (C-DQW) structure [7], shown in Fig. 2(a), where

ISB-T occurs at 1.5 μm and IB-T occurs at 1.3 μm. To the authors' knowledge, this has not been realized by other known materials. A 3.5-mm-long waveguide with 45-degree polished facets whose active layer is composed of a 93-period C-DQW structure was used in the experiment. The device was set in a 45-degree multiple reflection geometry, as shown in the inset of Fig. 2(b). An optical parametric amplifier pumped by a regenerative amplifier, which was seeded by a mode-locked Ti:sapphire laser, was used to produce 150-fs ISB-T resonant pulses (1.6 μm). IB-T resonant pulses, which covered the wavelengths ranging from 1.1 to 1.35 μm, were also generated via a sapphire plate. The IB absorption change induced by the ISB-T resonant light (Fig. 2) is integrated over the wavelength range from 1.28 to 1.32 μm; an ultrafast decay time as fast as 880 fs is achieved.

The transmission of the IB-T resonant light is shown in Fig. 3(a) as a function of the energy density of the incident ISB-T resonant pulses. Experimental results are denoted by the solid circles, and the fitted dashed curve is obtained from theoretical transmission calculations. Since our present device suffers from two-photon absorption, the absorption further increases at high input energy. The solid curve represents a fitted curve taking account of the two-photon absorption, which agrees well with the experimental results. For NOR logic, the transmission should be equally low for input powers of both $P_{\rm in}$ and $2\times P_{\rm in}$ to obtain a uniform zero output level. Also, the incident ISB-T power $P_{\rm in}$ should be as small as possible, while achieving a sufficient extinction ratio. Therefore, here we define a figure of merit (FOM) given by

$$\mathrm{FOM} = \frac{T(P_l) - T(P_h)}{P_h \times (T(2\times P_h) - T(P_h))} \tag{1}$$

where $T(P)$ shows the IB-T transmission at incident ISB-T power P, and P_l and P_h respectively represent the low and high ISB-T powers. The solid line with marks in Fig. 3(b) shows the FOM based on experimental results; it has a maximum at an ISB-T power (P_h) of 0.49 pJ/μm^2. At this operating point, the output signal levels are summarized as shown in the inset of Fig. 3(b); that is, the NOR truth table is accomplished. The extinction ratio is, however, very small in our present device (about 2 dB); this is currently being addressed by improving the design and fabrication of the device. Further improvement is also expected by employing a ridge (or mesa) waveguide structure with relatively high optical confinement instead of the 45-degree multiple reflection geometry, to increase the modulation efficiency. As shown in Fig. 3(c), the transmission may be improved by as much as 15 dB at an ISB-T input power of 0.49 pJ/μm^2 with a 200-μm-long waveguide, and its corresponding FOM will improve by as much as 25.

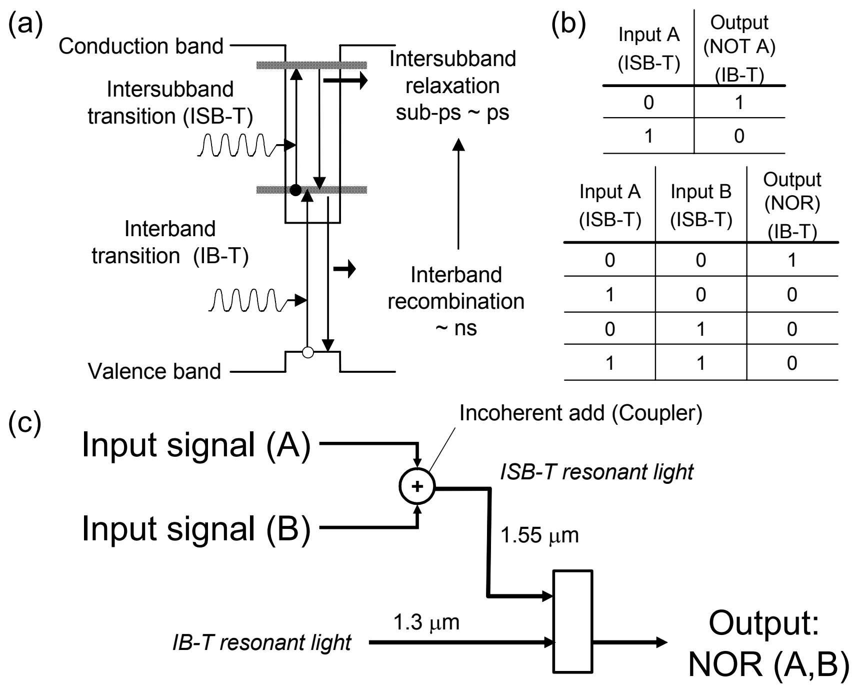

Fig. 1. (a) IB-T resonant light modulation by ISB-T resonant light [6]. (b) Truth tables of NOT and NOR gates.
(c) NOR architecture using ISB-T and IB-T.

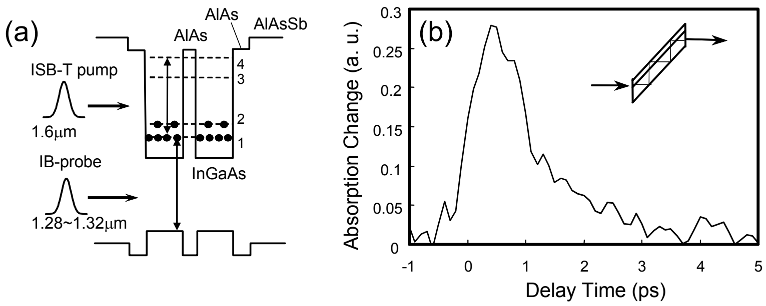

Fig. 2. (a) Band structure of the InGaAs/AlAsSb C-DQW. (b) Time evolution of the absorption change.

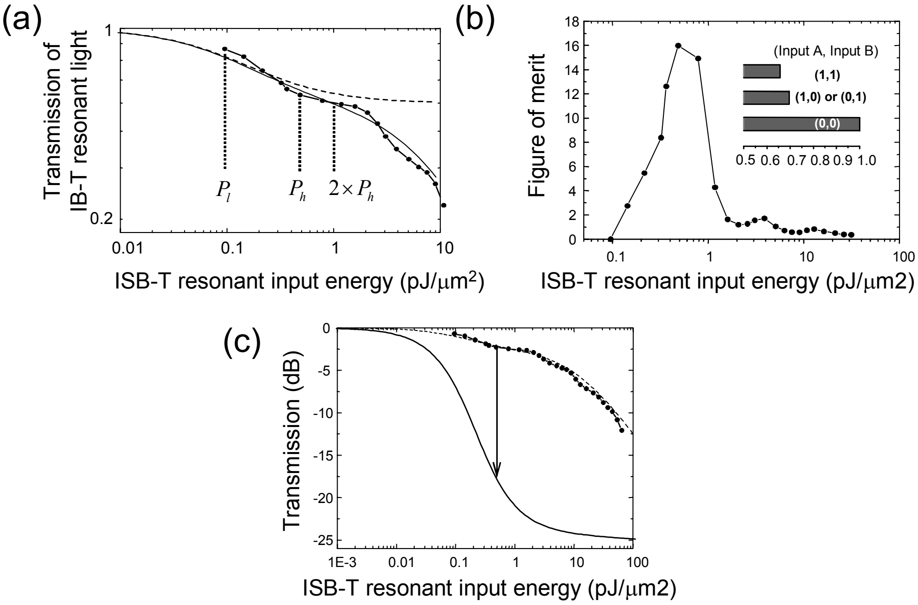

Fig. 3. (a) Transmission of IB-T resonant light as a function of ISB-T input energy density. (b) Figure of merit (FOM) defined by extinction ratio, operating power, and output level uniformity (defined in eq. (1)). Output signal levels at the maximum FOM (inset).
(c) Expected transmission improvement by using a waveguide structure.

4. Conclusion

In summary, an architecture for ultrafast all-optical digital processing, particularly NOR gates, based on ISB-T and IB-T in semiconductor quantum wells is proposed. Proof-of-principle experimental results and their analysis are also shown using InGaAs/AlAsSb C-DQW structures that allow operation at communication wavelengths. Part of this work is supported by the New Energy and Industrial Technology Development Organization within the framework of the Femtosecond Technology Research Project.

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