Optical and Electrical Control of Slow Light and Fast Light in Quantum-Dot Semiconductor Devices

Recently there has been great interest in slow light for optical buffer applications for future advanced optical network systems. The central idea is to design a “variable” optical delay device, which preferably is semiconductor-based and the group velocity of the optical signal can be controlled by an external pump laser or by an electrical bias. CONSRT researchers led by Prof. Chuang at UIUC have demonstrated room temperature fast light and slow light using quantum-dot (QD) semiconductor optical amplifiers (SOAs) with a GHz bandwidth.

Analog to the dispersive holographic recording and read-out in photorefractive crystals, a dynamic spatial gain and corresponding index gratings are introduced in QD-SOAs by counter-propagating optical pump and probe. The gratings induce coherent coupling of power from the pump into the probe and vice versa, and thus modify the group index of the probe beam in which optical signals are carried. The choice of QDs as active medium is determined to be 25 cm⁻¹. We use a 700 µm long QD SOA biased well above transparency current so the SOA is in a high gain regime. The spectral dip near the zero detuning corresponds to phase advance (fast light). The RF modulation frequency is 130 MHz.

The quantum-dot SOA is processed into a structure, as shown in Fig. 1(a), with the ridge-waveguide tilted 7 degrees related to the facet. The optical electroluminescence spectra at various biases are shown in Fig. 1(b). The active region of the SOAs consists of ten stacks of InAs/GaAs QDs with p-type doping in GaAs barriers. The net optical modal gain of the SOA is determined to be 25 cm⁻¹. We use a 700 µm long QD SOA (biased at absorptive regime) for slow light and a 2 mm one (biased as gain medium) for fast light. The heat-sink temperature is controlled to stay at 20°C.

As the 130 MHz modulated probe propagates along the 2.0 mm long quantum dot SOA, the phase delay of the light is found to be dependent on the detuning between the pump and probe, as shown in Fig. 2.

At an injection current of 300 mA, the spectral dip at zero detuning of the fast light corresponds to a group index reduction of 10% with a bandwidth of 13 GHz. In the case of slow light, the probe beam is modulated at 1 GHz. Fig. 3 shows a variation of the phase delay of the probe beam as a function of its detuning related to the pump. At zero current injection, a phase delay of about 2.5 degrees, equivalent to a delay time of 7 ps or a group-index increase of 3.0 is obtained. This time delay corresponds to a slowdown factor of 2 compared with that in a semiconductor or a factor of 6 compared to the speed of light in vacuum. Considering that the confinement factor is about 5% for the waveguide, the slowdown factor of the QD active region is estimated to be 40. The bandwidth of this delay is about 2 GHz. It is also demonstrated that the group index change can be controlled by electrical current injection and optical pump.

Since the devices are operated on a room-temperature semiconductor platform and require only electrical or optical pumping to control the slow light and fast light, their integration into practical optoelectronic systems is feasible. This type of all-optical delay lines may potentially overcome the O-E-O conversion bottlenecks in high speed optical information systems.

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Fig. 1 (a) On the left shows structure of our QD semiconductor optical amplifier.
(b) On the right shows the output spectra of a 700 µm long QD SOA under different current injection levels from 50 to 350 mA.

Fig. 2. RF Phase delay in a 2.0-mm long QD SOA biased well above transparency current so the SOA is in a high gain regime. The spectral dip near the zero detuning corresponds to phase advance (fast light). The RF modulation frequency is 130 MHz.

Fig. 3. RF Phase delay in a 0.7-mm long QD SOA with bias currents below the transparency current of 30 mA so the SOA is still in the absorption regime. The peak near the zero detuning corresponds to a phase delay (slow light) due to the optical pump. The RF modulation frequency is 1 GHz.