A Multiple-Output High-Speed All-Optical Demultiplexer Based on Low-Temperature-Grown Be-Doped Strained Multiple Quantum Wells

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Abstract

A novel high-speed all-optical demultiplexer with simultaneous multiple outputs is successfully demonstrated. The demultiplexer utilizes a compact, surface-reflection optical switch based on low-temperature-grown Be-doped strained InGaAs/InAlAs multiple quantum wells. 21.3-Gbit/s demultiplexing with two simultaneous outputs is achieved.

Introduction

Ultrafast all-optical demultiplexers are an essential element for future ultrahigh-speed time-division-multiplexed optical communication networks that are not limited by electronic bottlenecks. Different types of all-optical demultiplexers have been demonstrated that utilize various optical non-linearities [1]. Among these, those based on semiconductors are especially promising as they can result in devices that are compact and stable and, thus, practical. Semiconductor devices are, however, limited by too large carrier lifetime when resonantly excited. In an attempt to overcome this limitation, low-temperature-grown InGaAs/InAlAs multiple quantum wells (MQWs) have been investigated and it was found that their carrier lifetime can be reduced to the sub-psec range with a sufficient amount of Be-doping [2]. By using absorption non-linearities in such MQWs that were further enhanced by adding compressive strain and DBR mirrors, an ultrafast (1.5 psec switching time), 1.55-μm surface-reflection optical switch has been achieved that has high on/off ratio (13 dB), low switching energy (2 pJ), and polarization insensitivity under linearly polarized excitations [3]. Furthermore, a novel demultiplexing scheme based on this newly developed optical switch has been proposed [3]. In this paper, the successful experimental realization of the proposed all-optical demultiplexer is reported.

Experiments

Figure 1 schematically shows the operating principle of our demultiplexer. Incoming time-division-multiplexed *N*-channel signals with channel separation of τ are coupled into *N* different routes. Signals in the *n*th route are delayed by $n\tau$, and focused on the surface-reflection optical switch. This creates a temporal window where signals in all different channels overlap. If the gate pulse reaches the switch synchronized to this window, only those signals inside the window can be reflected from the switch. Once they are coupled out to output routes, we then have *N* simultaneously demultiplexed signals.

In order to demonstrate feasibility of the above scheme, an experiment was performed in which 21.3-Gbit/s signals were demultiplexed using a surface-reflection optical switch made of low-temperature-grown Be-doped strained InGaAs/InAlAS MQWs. The layer structure is shown in

Figure 2 and further details of epitaxial growth and layer structure can be found in [2, 3]. Figure 3 schematically shows the layout of the experiment. A commercially available optical-parameter-oscillator (OPO) pumped by a mode-locked Ti:Sapphire laser was used for short pulse generation. The OPO can produce short pulses with full-width-at-half-maximum (FWHM) of about 100 fsec, average power of about 250 mW, and repetition rate of 82 MHz. The peak wavelength of the pulses can be tuned from 1.34 to 1.60 μm. Short pulses generated by the OPO passed through a band-pass filter with peak transmission at 1.532 μm and bandwidth of 3 nm. After the filter, the pulses were broadened to auto-correlation FWHM of about one psec.

The pulses were then coupled into two separate fibers, one for the signals and the other for the gate. The signal pulses were introduced to a multiplexer which, with the proper combination of beam splitting and delaying, produced two identical trains of four multiplexed signals with 47-psec channel separation. One train of these multiplexed signals was delayed 47 psec by a delay unit so that its Channel 1 temporally overlapped with Channel 2 of the other train of pulses. The signals were then introduced to the demultiplexer unit composed of a sample holder and optical elements that allowed light from Port A (see Figure 3) to be reflected from the optical switch and coupled out to Port B, and from C to D. Presently, the demultiplexer unit has only two input and two output ports and, consequently, our experiment was limited to demultiplexing two out of four multiplexed signals. The gate pulse was synchronized by another delay unit and introduced to Port B of the demultiplexer unit through a 3-dB coupler. It was estimated that the sample was exposed to the gate and the signal pulses within a circular region of about 1.5-μm radius. Demultiplexed signals were then observed by a synchronously scanned streak camera.

Results and Discussions

Figure 4 shows the streak camera images of four-channel signals right after the multiplexer, and demultiplexed signals at different gate pulse energies. These images clearly demonstrate that 21.3-Gbit/s demultiplexing with two simultaneous outputs (Channel 1 and Channel 2) was successful with our proposed scheme. In principle, our demultiplexing scheme can handle as many channels as limited by input/output coupling with only one optical switch. Although such simultaneous multiple-output demultiplexing has been reported for fiber-based optical switches [4], we believe this is the first demonstration with semiconductor-based optical switches.

From the streak camera images, the signal on/off ratio can be estimated to be about 12 dB for the gate pulse energies of both 1.6 pJ and 2.6 pJ, but reliable estimation cannot be made for higher energies. In order to determine on/off ratios more accurately than is possible with the streak camera images and to project the possible demultiplexing performance at much higher speed than the present 21.3 Gbit/s, pump-probe measurements were performed. The experimental layout for pump-probe measurements was essentially the same as that shown in Figure 3. Instead of multiplexed four-channel signals, however, only one pulse entering Port C was used as the probe. Figure 5 shows the normalized intensities of the reflected probe pulses at two different pump energies as a function of probe pulse delay time with respect to the pump pulse. The reflected probe intensities show rapid turn-on but gradual turn-off characteristics that are associated with, respectively, generation and recombination of carriers inside MQWs. It can be also seen that higher energy pumping results in higher maximum on/off ratio but slower turn-off characteristics. In order to determine on/off ratios achievable at different demultiplexing speeds at different gate pulse energies, the ratios of intensities at peak to intensities at 10, 20, and 100 psec delays of the reflected probe pulses were determined for various pump energies and are shown in Figure 6. These ratios at 10, 20, and 100 psec delays would directly translate into on/off ratios for demultiplexing 100, 50, and 10 Gbit/s signals, respectively. It can be observed from Figure 6 that at 10 Gbit/s the ratio increases with higher pump energies whereas at 100 Gbit/s the ratio peaks at around 2.6 pJ but drops beyond that. This observation indicates that 100-Gbit/s demultiplexing with better than 10 dB on/off ratio would be possible with our demultiplexing scheme. In the present experiment, direct demonstration of such ultrafast demultiplexing was not possible due to lack of resolution in our streak camera as well as the multiplexer.

Conclusion and Acknowledgment

A novel all-optical demultiplexer that is fast, compact and provides simultaneous multiple outputs was achieved at 21.3 Gbit/s based on a low-temperature-grown Be-doped strained InGaAs/InAlAs MQW surface-reflection optical switch. From the pump-probe measurement results, further improvements in demultiplexing speed are expected. The authors would like to thank Dr. T. Mizutani for his continuous encouragement.

References

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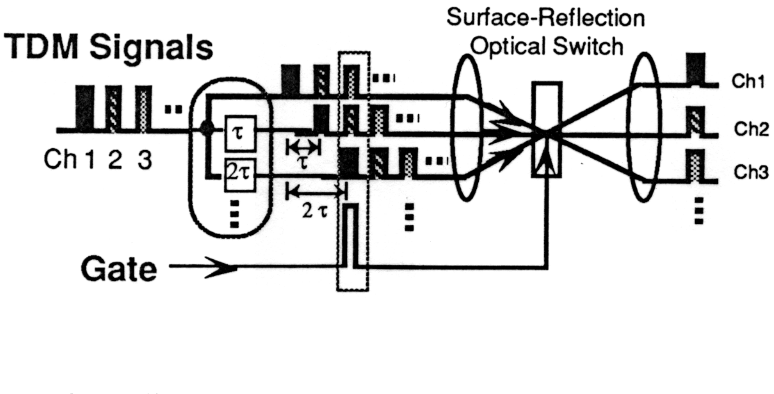

Fig. 1 Illustration for the proposed demultiplexing scheme.

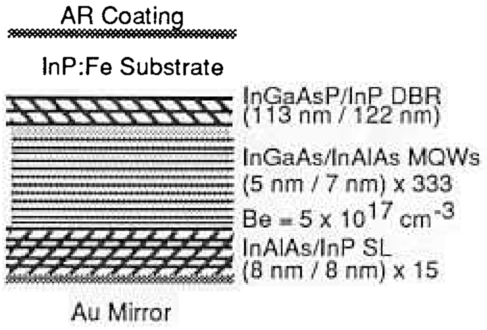

Fig. 2 Layer structure of surface-reflection optical switch used in the experiment.

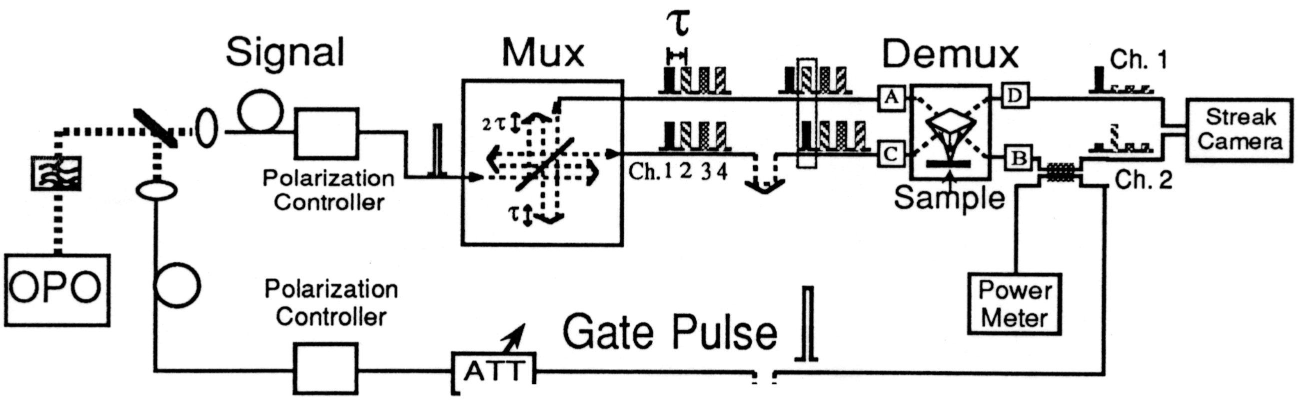

Fig. 3 Experimental set-up for all-optical demultiplexing with simultaneous two channel outputs.

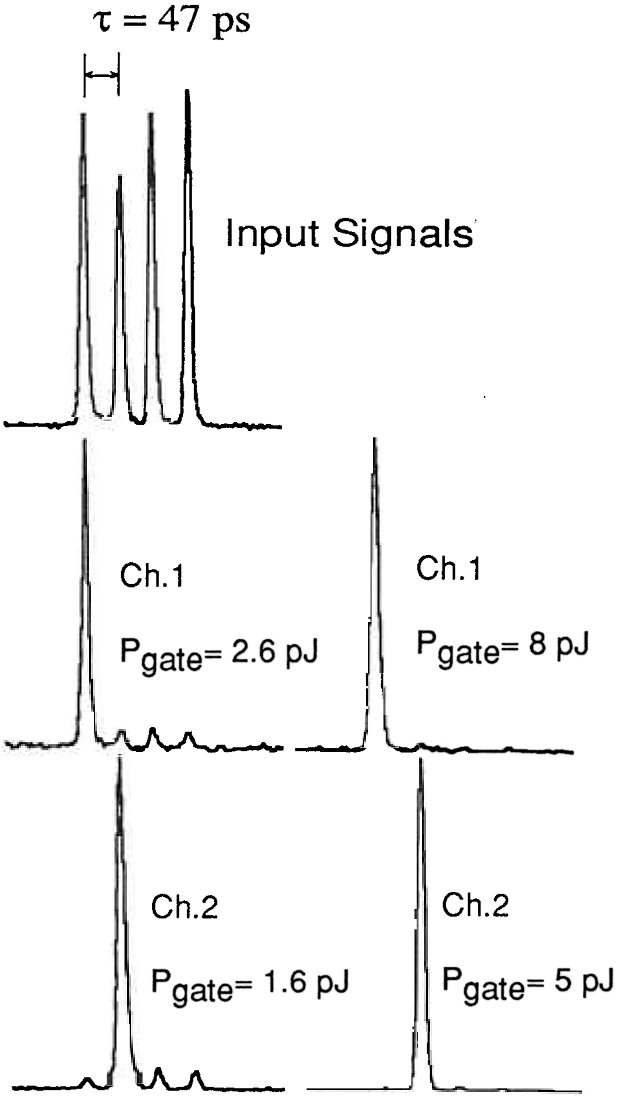

Fig. 4 Streak camera images of input and demultiplexed signals from channel 1 and 2 at various gate energies.

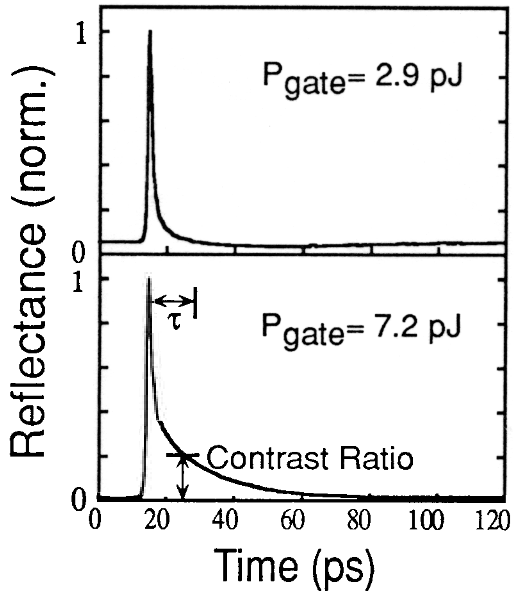

Fig. 5 Time-resolved probe reflectance at different gate pulse energies

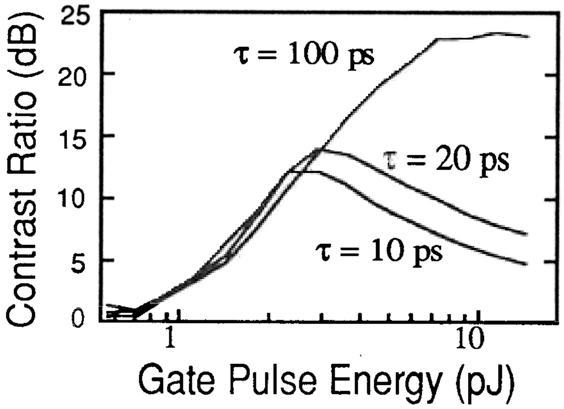

Fig. 6 Dependence of contrast ratios on gate pulse energies at various delay times. The contrast ratios are determined from the time-resolved reflectance as shown in Fig. 5.