All-Optical Wavelength Conversion at 160Gb/s by Intersubband Transition Switches Utilizing Efficient XPM in InGaAs/AlAsSb Coupled Double Quantum Well

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Abstract *We report all-optical wavelength conversion of 160-Gb/s signal by intersubband transition switches with signal pulse energy as low as sub-pJ, which is enabled by newly designed InGaAs/AlGaAs/AlAsSb coupled double quantum wells exhibiting the enhanced cross-phase modulation.*

Introduction

Intersubband transitions (ISBT) in semiconductors quantum wells have a potential application to all-optical signal processing for high-bit-rate (above 160 Gb/s) optical fiber communication systems at λ~1.55 μm. A unique property of ISBT for this application is very short intersubband carrier relaxation time of the order of sub- to a few picoseconds (ps) due to efficient emission of longitudinal optical phonons. It is a few orders of magnitude faster than interband carrier recombination time. This can be applied to ultrafast nonlinear optical devices. Especially in InGaAs/AlAs/AlAsSb coupled double quantum wells (CDQWs), a novel modulation mechanism has been found, in which TE light immune to the absorption is phase-modulated by ISBT excitation by TM light[1,2]. This is interesting modulation mechanism, since TE light does not suffer from a large insertion loss due to the ISBT absorption. All-optical signal processing such as wavelength conversion at 10 Gb/s [2], demultiplexing from 160 Gb/s to 10- and 40 Gb/s [3], and a sinusoidal phase modulation at 76 GHz in the ultra-wide spectrum range (~300 nm)[4] has been demonstrated. In this contribution, we report all-optical wavelength conversion at higher bit rate of 160 Gb/s by using a Mach-Zehnder Interferometer (MZI) ISBT switch. In this MZI-ISBT switch, InGaAs/AlAsSb CDQWs with AlGaAs coupling barrier enhances cross-phase modulation (XPM) efficiency up to ~0.5 rad/pJ, by which higher bit rate operation has been achieved.

Experimental

The wafer for the waveguide was grown on an InP substrate. The epitaxial layers consists of a 0.63-μm-thick active layer of a 65 period of $In_{0.8}Ga_{0.2}As$(3nm) /$Al_{0.5}Ga_{0.5}As$(0.57nm)/$In_{0.8}Ga_{0.2}As$(3nm)/AlAs(0.57nm)/AlAsSb(2nm) /AlAs(0.57nm) CDQWs (Fig.1(a)), followed by a 1-μm-thick AlGaAsSb upper cladding layer. The carrier density in Si-doped InGaAs well layers is $2.5\times10^{18}/cm^3$. A high-mesa waveguide with ~1μm-wide and 250-μm-long was fabricated by dry-etching. In the waveguide transmittance spectra, the TM spectrum shows that an intersubband absorption band (e1-e4) covers the entire C-band spectral range, while the TE mode is transparent at this spectral range, and an interband absorption (e1-hh1) edge locates at λ =~1.48μm. (Fig.1(b)) The CDQWs structure is designed to enhance the XPM efficiency up to ~0.5 rad/pJ [5] due to the interband dispersion effect[6].

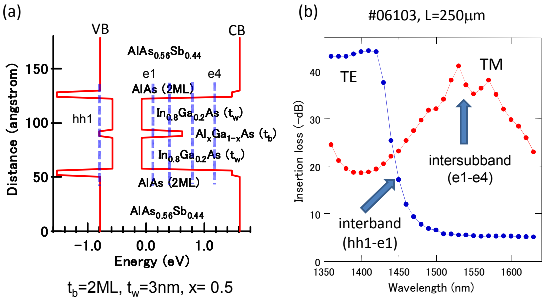

Fig.1: (a) band diagram of InGaAs/AlAsSb CDQW, (b) fiber-to-fiber insertion loss of the waveguide.

The experimental set-up of all-optical wavelength-conversion is shown in Fig.2. A 10-GHz actively mode-locked fiber laser (MLFL) with pulse width of 2 ps and wavelength of 1559 nm was used as a light source of signal. The optical pulse train from the

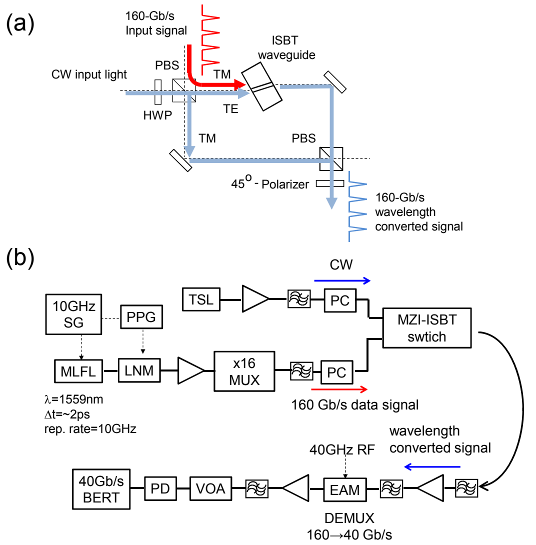

Fig.2: (a) Schematic layout of MZI-ISBT switch. (b) experimental set-up of all-optical wavelength conversion of 160 Gb/s signal.

978-3-8007-3173-2

MLFL is data-coded at 10 Gb/s with a pseudo-random bit sequence (PRBS = 2^7-1) using a lithium niobate intensity modulator. Then, the 10-Gb/s signal is multiplexed to generate 160 Gb/s using a fiber-based multiplexer. The amplified data signal and a continuous wave (cw) light are input into the MZI-ISBT switch module[3,4]. The polarization of the data signal is adjusted at TM mode to excite the ISBT (e1-e4) in the QW. A wavelength-converted signal is obtained from XPM sideband appeared around the CW input light frequency, while cw component is suppressed by adjusting a phase bias of the MZI. The wavelength-converted signal was directed to a 40-Gb/s bit-error rate tester (BERT). A demultiplexer based on electro-absorption modulator (EAM) was used to extract a 40 Gb/s tributary channel from 160-Gb/s wavelength-converted signal before sending it to 40-Gb/s BERT.

Results and Discussion

Figure 3 (a-c) shows the eye diagrams of 160 Gb/s input signal (a), the wavelength converted 160 Gb/s signals (b), and a 40 Gb/s tributary (c) in the 160 Gb/s wavelength converted signal after demultiplexing by the EAM. These eyes were measured by a 70 GHz photo diode with a 100 GHz electrical sampling oscilloscope. In this experiment, the input signal pulse energy of 0.73 pJ/pulse (average power of 57.8 mW) and cw light power of 10 mW are injected into the MZI-ISBT switch module. Although eye patterns of 160 Gb/s input and output signals are broadened due to the limited band width of the oscilloscope, they appear similar eye quality, indicating high performance operation with no pattern effect in the wavelength converted signal. A clear and open eye is observed for the 40 Gb/s tributary in the 160 Gb/s wavelength-converted signals as seen in Fig.3 (c). Figure 3 (d) and (e) shows the optical spectra of the 160 Gb/s wavelength converted signal and a 40 Gb/s tributary corresponding to eye diagram in Fig.3(b) and (c), respectively. The spectra in the wavelength converted signals consist of sharp peaks with 160-GHz (d) or 40GHz (e) spacing and a broad continuum band, confirming of 160 Gb/s and 40 Gb/s RZ signals.

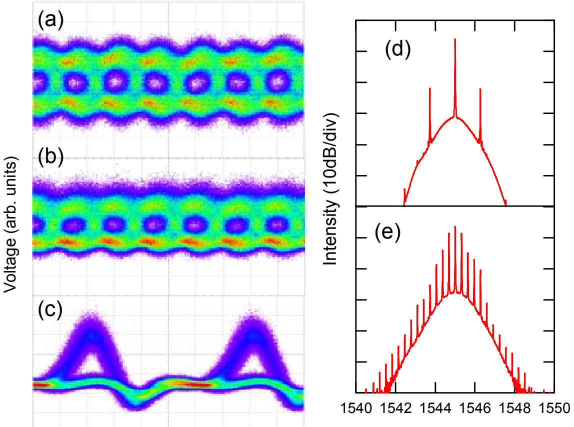

Fig.3: Eye diagram of (a) 160 Gb/s input signal (λ=1559 nm), (b) 160 Gb/s wavelength converted signal ((λ=1545 nm), (c) 40 Gb/s tributary after demultiplexing of the converted signal. Spectra of 160 Gb/s wavelength converted signal (d) and 40 Gb/s tributary (e).

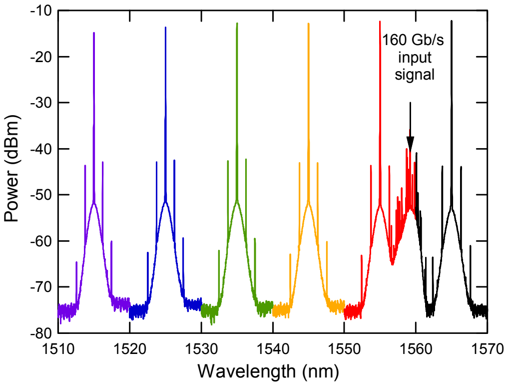

Fig.4: Output spectra of cw light accompanied with XPM side band. The 160 Gb/s input signal wavelength is 1595 nm.

Next, a spectral band width in the wavelength conversion is examined. Figure 4 shows the output spectra of phase modulated cw light, in which the polarization of cw input light is adjusted such that the whole power is directed into the waveguide arm in the MZI. The wavelength and pulse energy of the 160 Gb/s input signal are 1559 nm and 0.73 pJ/pulse, respectively, while the cw light wavelength is varied over the entire C-band spectral range. As seen in the Fig. 4, the relative intensity of XPM sideband respective to the CW component is almost unchanged over the C-band. Therefore the performance of the wavelength conversion similar to the result in Fig.3 can be expected for any target wavelength in this spectral range.

Conclusion

We have reported all-optical wavelength conversion at 160 Gb/s by using MZI-ISBT switches with input signal as low as sub-pJ pulse energy. This was enabled by enhanced XPM efficiency using a newly designed InGaAs/AlGaAs/AlAsSb coupled double quantum wells with enhanced XPM efficiency.

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