All-optical Wavelength Converter and Monolithically Integrated Switch Based on Electro-absorption Nonlinearity

電界吸収非線型効果を用いた波長変換器およびモノリシック集積型全光スイッチ

THESIS

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Abstract

The tremendous development of the internet or other wide band access technologies such as DSL、FTTH has driven the development of the high-capacity optical networks from research laboratories into commercial deployment such as Synchronous Optical Networks (SONET) or Synchronous Digital Hierarchy (SDH). In the first generation, optics is used only in transmission, and all switching and other intelligent functions are handled in electronics. Now people are seeing the deployment of the 2nd generation optical networks, where some of the routing, switching and intelligence are handled optically. In this network, data is carried from its source to its destination in optical form, without undergoing any optical-to-electrical conversion so that the electronic devices will not limit the speed. In this network, both of the two current primary techniques for data multiplexing i.e. wavelength-division multiplexing (WDM) and time-division multiplexing (TDM) are used including all optical devices such as wavelength converters, all optical switches, optical add/drop multiplexer, 2R, 3R and etc..

This thesis introduces two novel devices for all optical processing by using multiple quantum well (MQW) electroabsorption modulators (EAM) for high-speed telecommunication: wavelength converters and all optical switches. The reasons why the EAM is used to replace the traditional semiconductor optical amplifier (SOA) are short recovery time under reverse bias (possible to be <10ps), high stability, no amplified-spontaneous emission (ASE), and easy integration with other devices, especially, lasers. Moreover, we chose InGaAlAs as the core layer material in our devices due to its merits of large refractive index ratio between waveguide and cladding layer, large conduction band offset suitable for uncooled operation, and large spectral range.

The proposed wavelength conversion is based on the optical nonlinear polarization rotation in an EAM. Nowadays, most of the EAM-based wavelength conversion is using cross-absorption modulation (XAM) due to its simple configuration. However, XAM suffers from the large input power, typically larger than 15dBm. In order to reduce the input power, we investigate the cross-phase modulation (XPM) for TE mode and TM mode, and the polarization rotation. In the static wavelength conversion experiment, we demonstrated that the input powers for π phase shift are only 5dBm for upward conversion (from 1555nm to 1560nm) and 8dBm for downward conversion (from 1555nm to 1550nm), and the extinction ratios are 34dB and 31dB respectively. 10Gb/s dynamic wavelength conversion has also been demonstrated. Further simulation shows that the narrowing of the quantum well and

compressive strain of MQW enhance the polarization rotation, thus reducing the required input power for saturation state. Higher speed operation is also possible by using higher reverse bias voltage and optimizing the RC response.

For all optical switches, a Mach-Zehnder interferometer (MZI) configuration with EAM on the MZI arms is proposed. On account of the low relaxation time of EAM, no push-pull operation is needed. Moreover, compared to SOA, EAM has no current injection, so lower heating and low power consumption can be achieved. The static wavelength conversion has been demonstrated in the high mesa a MZI-EAM all-optical switch, but due to the large insertion loss caused both by the sidewall roughness of the mesa and the doping in the cladding InP, the dynamic operation is difficulty. Compared to this, switches with ridge waveguide is superior for low loss (20dB reduction). The 2.5Gb/s wavelength conversion has been demonstrated, though all the performances need to be improved by optimizing the MMI for better balance.

The main challenge of our MZI-EAM device is the monolithic integration of the EAM and other passive waveguide. Due to large insertion loss of EAM and no gain devices in the whole structure, etch and regrowth method is chosen to reduce the total insertion loss by optimizing the active and passive regions individually. Till now, etch and regrowth technology has been well developed for InGaAsP material, but for Al-containing material, it still remains a challenge, especially for ex-situ cleaning procedure. The difficulty arises from the formation of stable Al-Oxides due to the often inevitable air-exposure of the InGaAlAs core layer during device processing, which degrades the crystal quality grown at the interface and causes large scattering loss. We optimized the growth conditions by MOVPE and fabrication process for both one-step regrowth and two-step regrowth and obtained good connection at the interface of the passive waveguide and active EAM region, with high coupling efficiency and low coupling loss (0.21dB/facet).

Another big issue of the EAM-based all optical switch is the large insertion loss. This is mainly due to the large absorption of EAM and scattering in the waveguide. High mesa structure is superior for small size, but suffering from the significant scattering loss at the sidewall. Ridge structure has much lower loss, but has longer S-bend and multimode interferometer (MMI). Moreover, the doping profile in the cladding layer has also influence on the total loss.

Contents

Chapter I
Introduction

1.1 Background

The tremendous development of the Internet or other wide band access technologies such as DSL, FTTH has driven the development of the high-capacity optical networks from research laboratories into commercial deployment such as Synchronous optical networks or Synchronous digital hierarchy. In the first generation, optics is used only in transmission, and all switching and other intelligent functions are handled in electronics. Now people are seeing the deployment of the 2nd generation optical networks, where some of the routing, switching and intelligence are handled optically. In this network, data is carried from its source to its destination in optical form, without undergoing any optical-to-electrical conversion so that the speed will not be limited by the electronic devices.

In order to provide the capacity needed to realize the optical network, two fundamental multiplexing techniques are used, as shown in Figure 1.1.

The first is to increase the bit rate. Many lower-speed data streams are multiplexed into a higher-speed stream at the transmission bit rate by means of time division multiplexing (TDM). The multiplexer typically interleaves the lower-speed streams to obtain the higher-speed stream.

The other way to increase the capacity is by a technique called wavelength division multiplexing (WDM). The idea is to transmit data simultaneously at multiple carrier wavelengths over a fiber. To first order, these wavelengths do not interfere with each other, thus WDM provides "virtual fibers", in that it makes a single fiber look like multiple "virtual" fibers, with each virtual fiber carrying a single data stream. WDM systems are widely deployed today in long-haul and undersea networks and are being deployed in metro networks as well.

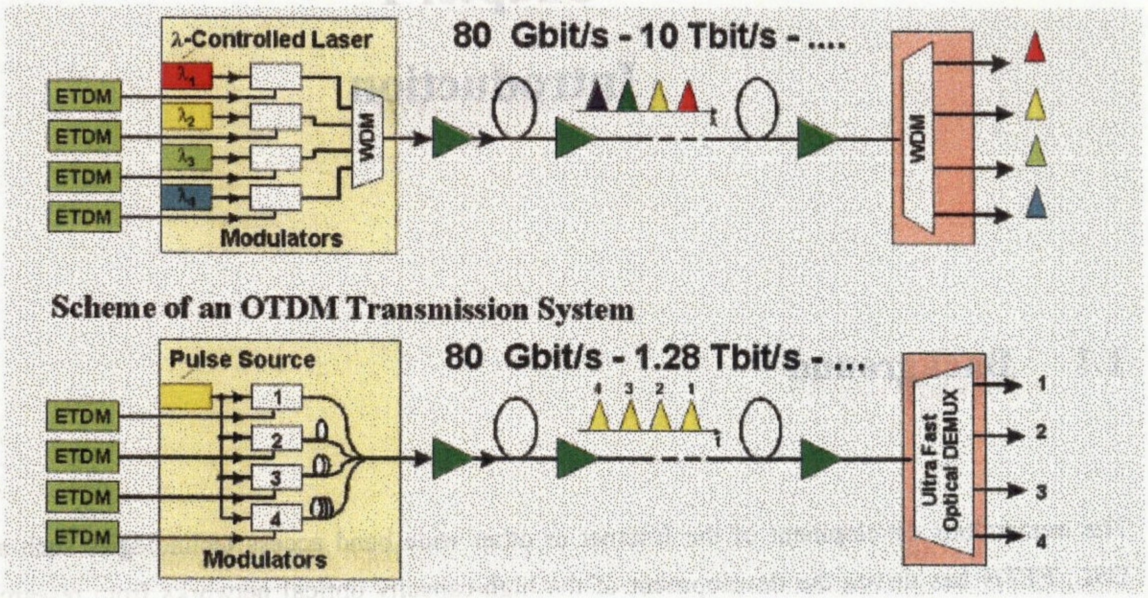

Fig.1.1 Schemes of the OTDM and DWDM transmission system [1].

Recently, 5.12- and 3-Tb/s transmission by combined OTDM (optical time division multiplexing) and WDM (wavelength division multiplexing) (128x40Gb/s, 19x160Gb/s) has been successfully demonstrated [2][3]. These systems require ultrafast signal processing like optical demultiplexing, add/drop functions, and wavelength conversion. Meanwhile, not only the "ultrafast" signal processing unavoidably needs "all-optical" to break through the bottleneck of electronic circuits, but also the cost-effective fiber communication system needs the "all-optical" to reduce O/E (opto-electronic conversion) and E/O (electro-optic conversion) pairs, even the electronic devices are fast enough. In the following section, we will discuss several solutions for all optical processing.

1.2 All optical processing

Devices for all-optical signal processing exploit ultrafast nonlinear effects to control light with light. This means that an optical control signal selectively changes the properties of a nonlinear medium such as to influence the optical data signal in a desired manner. The advantage of the all-optical way of data processing is the tremendous speed benefit compared to electronic solutions, which are mostly limited by inherent RC time constants and the carrier dynamics of the electronic components. The goal of all-optical signal processing is the avoidance of limiting electronics until the data reaches its destination.

Various kinds of optical nonlinearity are possible to be utilized for all-optical processing, although there is a significant problem of tradeoff between required optical power and response speed. For example, Kerr effect induced in silica fiber has subpicosecond response, but its efficiency is quite low and it requires several hundred milliwatt class optical pump power to induce phase shift large enough to be utilized for wavelength conversion [4], [5]. On the other hand, a semiconductor optical amplifier (SOA) is superior in efficiency due to its gain, and wavelength conversion with a few or submilliwatt class pump power is possible [6], [7]. However, its response time is in the order of a few tens of picoseconds. The optical nonlinearities induced in an electroabsorption modulator (EAM) have a faster response than those induced in an SOA and a higher efficiency than those in silica fiber. In this section, we separately introduce all-optical signal processing in fiber based, SOA based and electroabsorption (EA) modulator based devices.

1.2.1 Fiber based All-Optical Signal Processing

Optical fiber based all-optical signal processing includes exploiting cross phase modulation (XPM), four-wave mixing (FWM), super-continuum (SC), and so on.

The first practical all-optical demultiplexing for OTDM signals was demonstrated [8] [9] with XPM in fiber based devices, named NOLM (nonlinear optical loop mirror) [10], which constitutes a Sagnac interferometer with a 3dB coupler. Since the first error free demultiplexing was reported in [11], great progress has been achieved with NOLM in the past decades. 640Gb/s OTDM DEMUX (demultiplexing) operation has been achieved by a specially designed NOLM DEMUX, using dispersion-flattened fibers with no walk-off between signal and pump pulses [12], and DEMUX on 1.28Tbps signals with 2 perpendicular modes each with 640Gbps OTDM in [13]. Latest development with NOLM constitutes shorter loop with highly nonlinear fibers. 40Gbps wavelength conversion was demonstrated in [14] with 1km highly nonlinear dispersion shifted fiber (HNL-DSF). 320Gbps OTDM DEMUX was achieved with shorter 100m HNL-DSF in [15]. And finally, with latest improvement in photonic crystal (PC) fiber, 160Gbps error free DEMUX operation was demonstrated with only 50m's long PC fiber in NOLM [16]. Recently, regeneration properties were also found with NOLM configurations. The first numerical demonstration was reported in [17], where in-line NOLM was found to achieve all-optical passive regeneration. Further numerical demonstrations of its application in WDM system were reported in [18]. Experimental demonstrations were done in [19] by other groups.

OTDM demultiplexing with exploiting FWM was first demonstrated in [20] from 16Gbps to 4Gbps, and later with multiples of 100Gbps [21]. FWM combined with super-continuum (SC) light source was reported in [22], where simultaneous error free DEMUX of OTDM channels to 8 WDM channels were demonstrated with FWM effect. Regenerative properties of FWM operation where pump light is modulated were also reported [23]. Other all-optical signal processing includes SBS (stimulated Brillouin scattering) for optical clock recovery [24] (not retiming), with a DSF optical loop.

Fiber based all-optical signal processing is a promising and still an irreplaceable technique in such as super-continuum generation, polarization related manipulation, however, generally speaking, the small nonlinear coefficient compared to semiconductor devices resulted in the large size of them, and poor integratability.

1.2.2 SOA based All-Optical Signal Processing

The all-optical signal processing based on semiconductor optical amplifier (SOA) is versatile. Based on four-wave mixing (FWM), cross gain modulation (XGM) and cross phase modulation (XPM), functions of all-optical wavelength conversion, OTDM, DEMUX, 2R or 3R regeneration, and logic gate are demonstrated. FWM was used in DEMUX for OTDM in relatively early stage for 20Gbps [25], and soon achieved 100Gbps DEMUX in [26], and 200Gbps [27]. Multiple channel output OTDM DEMUX using multichannel FWM was demonstrated in [28] for 100Gbps DEMUX. For increasing the conversion efficiency of FWM, dual-pump wave mixing was demonstrated for OTDM DEMUX [29]. Lately, 160Gbps DEMUX down to 40Gbps was demonstrated, for the future 40Gbps based electronics circuits. Theoretical analysis focused on OTDM DEMUX using FWM was reported in [30]. Intriguing regenerative properties of wavelength converter with FWM was also demonstrated [31]. Cross gain modulation (XGM) and cross phase modulation (XPM) simultaneously occur in an SOA, related by the Kramers-Krönig's relations. Following reports are mostly based on these two inter-band transition related phenomena, except for a few based on self gain modulation (SGM).

Although XGM and XPM related with inter-band transition in SOA suffer from relatively long gain recovery time dominated by carrier lifetime, several techniques were proposed in the year

1993, to speed up signal processing based on XPM in SOA. They are SLALOM (semiconductor laser amplifier in a loop mirror) [32], TOAD (terahertz optical asymmetric demultiplexer) [33], and SMZ (symmetric Mach-Zehnder interferometer) all-optical switch [34]. Later devices like UNI (ultrafast nonlinear interferometers) [35] are a kind of derivation of SMZ. The common point of these devices is canceling the relatively long carrier recovery time with delayed configuration in two paths of either Sagnac interferometer or Mach-Zehnder interferometer.

Generally, the operation speed of SLALOM and TOAD is slower than that of SMZ, resulting from its partial counter-propagation configuration of control light and signal light. For example, for achieving Teraherz operation following the name of TOAD, the length of the nonlinear material (SOA) should be less than 50μm, which imposes a strict limitation on the devices, while for SMZ configuration, no such limitation is imposed since signal and control light is always co-propagating.

It has been demonstrated both theoretically and experimentally, that SMZ type devices work faster than SLALOM or TOAD using Sagnac interference, and many reports has been done with SMZ type devices [36] [37]. Although most DEMUX operation was focused on one channel output, DEMUX from 40Gbps down to 4x10Gbps WDM was reported in [38], and first 40Gbps down to double 20Gbps output was reported without power penalty in [39]. In the single channel output DEMUX for OTDM signals, Mach-Zehnder interferometer switches have demonstrated up to 160Gb/s [40], and record 336Gbps in SOA-based devices. Functional SMZ switches are also reported these years, including control-signal separation scheme, ideal extinction ratio for both output ports with functional multimode interference (MMI) devices [41].

Wavelength conversion with Mach-Zehnder interferometer includes the first report in [42] with SMZ configuration, and record 168Gbps in [43] by NEC. Delayed-interference configuration with only one SOA demonstrated 100Gbps wavelength conversion although the data format changes after the conversion [44].

Logic gates were reported for XNOR gate with Mach-Zehnder interferometer configuration with 10Gbps in [45], AND gate with XPM in [46], half-adder XOR in [47], and XOR with self-phase modulation with 2.5GHz in [48].

SOA-based 2R or 3R regeneration has been achieved in various configuration, including using

Sagnac, Michelson or Mach-Zehnder interferometer, and single SOA, MMISOA, and etc. 3R regeneration with SOA in a fiber-sagnac interferometer was demonstrated in [49]. 3R regeneration with monolithically integrated delayed-interference configuration was reported in [50], and furthermore, 40Gbps cascaded wavelength conversion in a loop over 1e+6 km was reported in [51], owing to its regenerative properties. Alcatel also reported 40Gbps regeneration over 20000km in a loop [52]. 2R regeneration was reported with gain-clamped SOA in MZI configuration [53]. Penalty-free and error-free all-optical data pulse 2R regeneration at 84Gb/s was reported by NEC group in [54]. First 2R regeneration with Michelson interferometer was reported in [55].

Relative timing extraction was reported with using a single SOA in an open-loop feedback system [56]. MMI-SOA was reported to have 2R regenerative properties in [57], where the transfer function of MMI-SOA reveals a digital transfer characteristic and a high increase in extinction ratio.

SOA-based all-optical devices are expected to play important roles in the future optical fiber communication network.

1.2.3 EA Modulator based All-Optical Signal Processing

Electro-absorption (EA) modulators were traditionally developed for external modulation for lasers, featuring small chirp, high speed, and good integration. Besides this traditional usage, more and more all-optical signal processing based on EA modulators are reported. Most of them exploit the cross absorption modulation (XAM) and self absorption modulation (SAM), where absorption coefficient in EA saturates with input of other strong light, or the increasing power of it.

With strong nonlinearity in EA modulator, a simple pulse generation was proposed and demonstrated by using a sinusoidally driven InGaAsP EA modulator, and is widely used to date. By using the pulse compression effect due to nonlinear attenuation characteristics to the applied voltage to the modulator, a transform-limited optical pulse was generated just with only sinusoidal modulation on EA [58].

Regenerative properties of EA modulator were exploited for 2R (reshaping, reamplifying) and 3R (reshaping, reamplifying, retiming) regeneration. With using a reverse biased EA modulator, the nonlinear optical transmission characteristic of the EA reshapes the degraded input data by selective absorption of the optical noise and, therefore, increases the SN (signal-to-noise) ratio of the output. Wavelength conversion at 20 Gb/s with 2R was reported in [59], and furthermore, 2R before receiver of 10-Gb/s RZ data transmitted over 30 000 km was reported in [60]. 3R regeneration was developed by adding the feedback of the repetition rate error signal between data and clock to the driving RF (radio frequency) of a mode-locked laser diode (MLLD) [61].

Besides regeneration functionality, operation focused on wavelength conversion was also reported, where the input signal wavelength was simultaneously converted to six different wavelengths at 10 Gbit/s, named multicasting [62]. Logic "and" gate was achieved with EA modulator in [63], and label encoding as well as wavelength conversion was reported in [64].

More and more applications based on EA modulator are now developed, and further development is expected, however, due to the relatively large insertion loss, EA modulator is limited in the integration for large scale photonic integrated circuits (PIC), compared to the semiconductor optical amplifier (SOA) with the function of amplification.

1.3 Research purpose

From the previous sections, EAM has advantages in all optical processing. However, till new, most researches focus on the XAM. XPM has seldom been investigated. Therefore, The purpose of this research is investigate the XAM and XPM effects of EAM in all optical processing devices including wavelength converters and all optical switches. On account of the advantages of InGaAlAs material in the uncooled laser and potential of the EAM with Laser, the InGaAlAs material is applied in the MQW structure.

1.4 Overview of the dissertation

Chapter II starts by briefly introducing the MOVPE. In our case, we chose the InGaAlAs material system in the MQW structure in the EAM. Therefore, the growth and optimization by MOVPE for this special material are described. Then three strategies for monolithic integration are compared. As for our approach, the butt-joint technology is chosen and discussed in detail.

In chapter III, we first simulate the MQW structure to show the basic performance of the EAM. Then the fabrication of the EAM is shown and the characterization of the EAM are given, including the measurement of photocurrent, electroabsorption modulation and nonlinear XAM and XPM.

In chapter IV, a novel wavelength converter proposed in our lab is introduced and the static and dynamic operations are demonstrated. In order to decrease the optical power, the strain effects are discussed theoretically.

In chapter V, a novel all-optical switch is proposed and the static and dynamic operations are demonstrated. Finally, the conclusion and more considerations will be given in chapter VI and chapter VII respectively.

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