이학박사학위 청구논문

광신호 처리를 위한 광소자들의 특성 측정 및 응용 연구

Characterization and Applications of Photonic Devices for Optical Signal Processing

인하대학교 대학원

물리학과 (광학전공)

이 승 훈

2011년 8월
Characterization and Applications of Photonic Devices for Optical signal Processing

by

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A THESIS
Submitted to the faculty of
INHA UNIVERSITY
in partial fulfilment of the requirements
for the degree of
DOCTOR OF PHILOSOPHY

Department of Physics
May 2011
이 논문을 이승훈의 박사학위 논문으로 인정함.

2011년 5월 31일

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Abstract

This thesis focuses on study of basic photonic devices related to long-wavelength single-mode vertical-cavity surface-emitting lasers (VCSELs) and single-photon detectors for applications to high-speed signal processing and quantum communications as well as characterization of nonlinear optical materials for such applications.

New simple interferometric method for measuring the second-order nonlinear optic properties of optical materials were proposed and demonstrated by confirming the known electro-optic (EO) coefficient of the lithium niobate crystals. This method was intended to measure the EO coefficient of new polymer materials for periodic poled devices for quantum entangled photon generation. In addition, a method of third order nonlinear coefficient and zero-dispersion wavelength of a highly nonlinear fiber was also demonstrated as a part of four-wave-mixing based entangled photon generation.

1.5-μm wavelength single-mode VCSELs were studied for timing-jitter reduced laser pulse generation, polarization bistability, and optical flip-flop operations. These measurements were expected to be useful for all-optical high-speed two-dimensional signal-processing as well as partly for pump laser sources generating quantum correlated photons via nonlinear effects.

Some works on the single-photon detectors and its application to quantum key distribution were also carried as parts of the quantum communication research. Low noise single photon detector based on InGaAs/InP APDs were developed and used for demonstration of quantum key distributions.

During the course of this study I have developed basis technologies and sciences for all-optical high-speed signal processing and quantum communications.
Acknowledgement

Above all things, I would like to give God the glory for this thesis.

I would like to express my deep appreciation to my advisor, Prof. Kyong Hon Kim, for his understanding, support, and guidance during the past six and a half years of my master and Ph. D. courses. It has been an honor for me to be his first Ph. D. student.

I would like to thank Prof. Min Hee Lee, Prof. Jae Woo Noh, Prof. Min Yong Jeon, and Dr. Byueng Su Yoo for taking their valuable time and providing helpful comments on this thesis. In addition, I would like to express my sincere appreciations to many good professors in department of physics, Inha University. Profs. Min Hee Lee, Jae Woo Noh and Kisik Kim have provided me valuable guidance during my academic life. Profs. Dongwoo Cha, Kiyoun Lee and Chang kwon Hwangbo gave me an opportunity to take their wonderful lectures in physics and optics courses.

I have many members in my laboratory and neighbor laboratories related to optics and photonics, to whom I would like to express my appreciations for their friendship and technical collaboration during my graduate student period. I want to thank Dr. Yoon Shik Kang, Dr. Chang Hyouck Lee and Mr. Hyoung Joo Kim for helpful exchange of their ideas and experiences. Special thanks need to be given to my colleagues of our Photonic Science Laboratory, Dong Seok Lee, Kyu Hyeon Jeong, Seok Hyun Hwang and Jin Joo Kim who were earlier members. In addition, I want to give many thanks to Seung Hwan Kim, Vijay M. Deshmukh, Dong Wook Kim, Hae Won Jung for their contribution and ideas in completing many coauthored technical papers. It is also a good opportunity for me to work with new laboratory members, Hyo-Geun Yun and Heung-Sun Jeong and their help provided during carry-out of some experiments is also appreciated.
I would like to thank to my parents and parents-in-law for all their devoted love and endless support. Without their patience and encouragement, this work could not be completed. Finally but most importantly I wish to dedicate this dissertation to my wife, Ho Eun Kim. Without her love and patience my graduate study could not be successful. In addition, this work was possible with my lovely children, Eun Soo and Joon Soo, whose smile and love motivated my daily life and gave me hope and encouragement even during my difficult time of course works and research period.
Publications

Journals

This thesis is based on the work contained in the following papers 1 to 7;


Conference Proceedings—International


Conference Proceedings-domestic


demonstration of long-range reflective-type optical displacement sensors,” The
Korean Physical Society fall annual meeting 2010, paper IB-19.
thermo-optic coefficients over a wide-wavelength range using a white-light
using a background subtraction method in a white-light interferometer,” COOC
2009, paper FP-21.
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The Optical Society of Korea 20th Anniversary Special Meeting 2009, paper WP-V14.
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15. S. H. Kim, S. H. Lee, and K. H. Kim, “Chromatic dispersion measurement of
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Korean Physical Society fall annual meeting 2008, paper IP-044.
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Optical Injection,” COOC 2007, paper TP-34.
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Registered Patents-domestic


Applied Patents-domestic


Applied Patents-International


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Chapter 1. Introduction

Advances in computer and internet technology in this information age allow high volume data storage and global communications available to our life. The rate of data transmission is growing exponentially. For example, the international standard of local area networks (LANs) is developed up to 100 Gb/s Ethernet, and the necessity of Terabit Ethernet is expected in 2015 [1]. However, conventional computing technologies and data communication networks based on metal wires has the limit in their operating bandwidths and transmission distances due to high power loss and significant heat generation. The photonic devices based on optical nature of medium are recognized as key solutions for such high speed signal-processing and communications. Recently, Intel presented an integrated photonic platform based on silicon photonic devices for 50 Gb/s data links, which contains silicon modulators, multiplexers and demultiplexers, and photodetectors with hybrid integrated laser sources [2].

Quantum information science has also emerged as a solution for problems related to dramatic increases of the computational power and the network security which are increasing concerns in recent information societies [3,4]. Recently, quantum key distribution systems have been recognized as an absolutely secure communication technology, and developed close to a practical application level. It is getting more obvious that high performance photonic devices and quantum optics will become important parts of future information ages.
This thesis focuses on study of basic photonic devices related to vertical-cavity surface-emitting lasers (VCSELs) and single-photon detectors for high speed signal processing and quantum communications as well as characterization of nonlinear optical materials for such applications. The timing-jitter reduced laser pulse generation, polarization bistability, and optical flip-flop operations based on long-wavelength VCSELs were studied for potential applications to all-optical high-speed two-dimensional parallel signal processing. Research on the single-photon detector and nonlinearity measurements was parts of quantum communication study. Measurement work of second-order nonlinear coefficients of optical materials was performed as a part of finding new electro-optic polymer materials for potential periodic-poled waveguide devices to generate entangled photons through the parametric-down conversion processes. During the course of this research we demonstrated a couple of new method of measuring second-order nonlinear coefficients of LiNbO₃ crystals, for which further research was still left for measurement of new polymers. Third-order nonlinear coefficient measurement of a highly-nonlinear fiber was done as a preliminary step to achieve entangled photon generation through a four-wave mixing process. In addition, some works on the single-photon detection and its application to quantum key distributions were also carried as parts of the quantum communication research. In this thesis I report some of technical progresses made on those topics. Nevertheless, those technical areas still require further researches in the future.

In chapter 2, a new interferometric measurement method carried out to determine second-order of nonlinear coefficients of LiNbO₃ nonlinear material
and a new four-wave mixing method to determine the third-order nonlinear coefficient and the zero-dispersion coefficient of a highly nonlinear fiber will be introduced. Chapter 3 reports low jittered pulse generation and polarization bistability of 1.5-μm wavelength single-mode (SM) VCSEL investigated for application to high-speed all-optical signal processing. The low-jittered optical pulses generated from a gain-switched VCSEL will be useful as pump sources to generate quantum correlated photons with reduced errors. In chapter 4, I will describe experimental results of low noise single photon detectors developed with InGaAs/InP APDs (SPADs) and of their application to the SPADs for demonstration of a two-way quantum key distribution system.
Chapter 2. Measurement of Optical Nonlinearities

Most of entangled photon pairs are based on optical nonlinear effects. Second-order nonlinear optic materials are used for the entangled photon generation through parametric down-conversion process, while the third-order nonlinear optic materials are used for the same purpose through the four-wave-mixing (FWM) process. Recently, efficient materials and photonic waveguide devices with high second order or third order nonlinearity are reported such as graphene [5], nonlinear polymer [6] and improved device structure based on quasi phase matching method [7]. Thus, an easy way to identify the nonlinear properties of new photonic materials is necessary. In this chapter, I will describe two new interferometric method and four-wave mixing methods measuring the second order and third order nonlinear coefficients.

2.1 Measurement of Dispersion of Electro-optic Coefficient

The knowledge of electro-optic (EO) coefficient of photonic materials is very important in many application areas, especially in areas of high-speed optical modulator and switch application. There have been many types of the electro-optic coefficient measurement methods, such as Mach-Zehnder interferometer method with a laser source and reference medium [8,9], an ellipsoid method of a thin sample with reflective coating or plate on its backside [10-13], an interference spectrum measurement method caused by multiple internal reflection within sample surfaces of a Fabry-Perot interferometer type [14], a
relative phase change measurement method between two orthogonally polarized beams passing through birefringent samples [15-17], a finite fringe interferogram method using a bulk-optics based Mach-Zehnder interferometer [18], and a direct EO modulation performance test method with an EO modulator made of sample material [19]. These methods have certain drawbacks because some of them measure the EO coefficient only at single wavelength, require a specially prepared geometry of the samples, or have a measurement accuracy limited by experimentally measurable parameters. Dispersion effect of the EO coefficient has been measured with a Mach-Zehnder interferometer method by Mendez, et al. [20] and with the multiple internal reflection method within the sample by Yonekura, et al. [21]. They used several discrete laser sources to measure the dispersion effect at discrete wavelengths. Especially the latter method required knowledge of the precise internal reflectivity to achieve an accurate EO coefficient as well as preferred high internal reflectivity. Knowledge of the dispersion effect of the EO coefficient is very important to EO modulators or switches suitable for wide wavelength range coverage.

In this section, a new simple method to measure the continuous dispersion spectrum of the linear EO coefficient using a white-light interferometry is described. This method is based on measurement of the phase changes of the white light interference patterns between with and without an electric voltage applied to the sample. Since the phase change is related to the EO coefficient of the sample, the low coherence interferometric method provides an accurate measurement of the EO coefficient over the whole spectral range of the low
coherence light source. This method can also allow a simultaneous measurement of unclamped EO coefficients of birefringent materials along their ordinary and extraordinary axes.

2.1.1 Experimental Setup and Theoretical Background

A schematic diagram of the experimental setup used for measuring the relative phase of the interference spectrum is shown in Fig. 2.1. The setup is based on a fiber-type Mach-Zehnder interferometer composed of two 50/50 fiber couplers with a broadband light source at its input side and an optical spectrum analyzer (OSA) at the output side. Each arm of the interferometer has a polarization controller and a pair of gradient index (GRIN) lenses for collimated beam transmission and reception. One arm of the interferometer, called “reference arm”, has an adjustable free-space spacer to change the spacing between the GRIN lenses, and the other arm, called “sample arm”, has a nonlinear crystal.

Figure 2.1 Experimental setup for measurement of the EO coefficient
sample with a pair of electrodes formed over its top and bottom sides in a perpendicular direction to the beam path to apply an electrical voltage across them. The broadband light source used in our experiment was a semiconductor optical amplifier (SOA) with a central peak wavelength at 1505 nm and a full width at half maximum (FWHM) of about 60 nm. We used a conventional z-cut congruent LiNbO₃ crystal (MTI corp.) with dimension of 10 mm × 10 mm × 0.5 mm, and the electrode was formed by Pt coating over an area of 7.8 mm × 7.8 mm at the bottom and top sides so that the electric field direction is located along the crystallographic z-direction [22]. Measurement errors for the crystal thickness and electrode length were less than 0.002 mm and 0.01 mm, respectively. An unpolarized white light beam was directed to propagate along the crystallographic y-direction so that the electric field was applied normal to the beam propagation direction. Two polarization controllers composed of single-mode fiber spooled pads, each of which was placed in the both reference and sample arms, respectively, were used to rotate the polarization states of the input beams for the maximum visibility of an output interference pattern. The reference arm was also adjusted to a fixed length so that the optical path length (OPL) along the reference arm was located between those of the ordinary and extraordinary waves in the sample arm in order to observe the combined interference patterns of the two polarized waves. Experimental measurements were first carried out with no electric voltage applied to the sample, and a phase-dependent interference spectrum caused by the difference of OPL between reference wave and ordinary/extraordinary waves in the sample arm.
was measured. Then, a similar interference spectrum with an electric voltage applied to the sample was measured.

The output beam intensity of the interferometer can be derived as

\[
I(\lambda) = |E_0(\lambda)|^2 + a^2|E_0(\lambda)|^2 + 2a|E_0(\lambda)|^2 \cos\{\phi(\lambda)\}
\]

\[= I_A + I_B + 2\sqrt{I_A I_B} \cos\{\phi(\lambda)\}, \tag{2.1}\]

where \(E_0\) is the electric field of the input beam entering the reference arm, and \(a\) is the ratio of the electric field magnitude of the input beam entering the sample arm to that to the reference arm [23]. \(I_A\) and \(I_B\) are the input beam intensities entering the reference and sample arms, respectively. \(\phi(\lambda)\) is the phase difference between the light beams passing the two arms without applied voltage, and is derived as

\[
\phi(\lambda) = \phi_f + \frac{2\pi}{\lambda} [L_{R,A} - L_{S,A} - n_0(\lambda)L_S]. \tag{2.2}\]

Here \(\phi_f\) is a phase difference between the light beams traveling over the fiber portions of the reference and sample arms. \(L_{R,A}\) and \(L_{S,A}\) are lengths of the air intervals in the middle parts of the reference and sample arms, respectively. \(n_0\) and \(L_S\) are refractive index and length of the sample which is a congruent LiNbO\(_3\) crystal in this experiment, respectively.

When an electric voltage \(V\) is applied across the thickness \(t\) of the sample, the index of refraction of the sample under an electric field \(E = V/t\) becomes

\[n(E) = n_0 + \Delta n = n_0 - \frac{1}{2} r n_0^3 E = n_0 - \frac{1}{2} r n_0^3 \frac{V}{t}.\]

Then, the phase difference between two arms \(\phi_{NL}(\lambda)\) under the applied voltage \(V\) becomes
In this equation \( r \) is the EO coefficient of the sample. If we subtract of Eq. (2.2) from Eq. (2.3), then we can obtain the follow equation for the EO coefficient:

\[
\phi_{NL}(\lambda) = \phi_f + \frac{2\pi}{\lambda} \left[ L_{R,A} - L_{S,A} - n_0(\lambda) L_S + r \cdot \frac{1}{2} n_0^3(\lambda) V L_S \right]
\]

(2.3)

(2.3)

The EO coefficient is related to shift of the phase difference between the two cases without and with an electric voltage applied.

### 2.1.2 Measurement and Data Processing

Fig. 2.2 shows a measured interferometer output spectrum and numerically analyzed data in a process to find the relative phase shift between the two cases without and with an applied electric voltage. Fig. 2.2(a) shows the measured interference spectrum of the Mach-Zehnder interferometer without an electric voltage applied across the sample in the experimental setup in Fig. 2.1. This optical spectrum contains two patterns caused by interference between each of the ordinary and extraordinary waves inside the birefringent sample and the wave through the reference arm. The measured interference spectrum was first subtracted by the spectral intensity emerging out through one of the sample and reference arms, when the other arm was blocked, which provided a resultant spectrum corresponding to last term of Eq. (2.1). Then, the wavelength domain
Figure 2. 2 (a) Measured interferometer output spectrum, and (b) an oscillation period curve of the interference signals calculated for the ordinary and extraordinary waves from the Fourier transformation of the spectrum in (a), (c) and (d) numerically separated interference spectra of the ordinary and extraordinary waves of a congruent LiNbO$_3$ crystal, respectively, under no applied voltage and (e) and (f) calculated relative phases vs. wavelength curves of the ordinary and extraordinary waves, respectively, for the cases without and with applied voltage.
spectrum is converted into a frequency-domain spectrum by using the relationship of \( f = \frac{c}{\lambda} \). A numerical Fourier-transformation is performed over the frequency-domain spectrum, and then two different peaks in time-domain, each corresponding to an oscillation period of the interference signal for the ordinary and extraordinary waves, respectively, appear as shown in Fig. 2.2 (b). Selection of each of the peaks with a bandpass filtering process and application of an inverse Fourier transform process to the selected one provide separation of the two interference spectra. Each of the separated interference spectra was then normalized by using the spectral intensity measured from each of the separate arms according to the last term of Eq. (2.1) in order to obtain a normalized interference spectrum corresponding to the pure cosine term. Fig. 2.2(c) and (d) show the normalized and separated interference spectra for the ordinary and extraordinary waves passing through the sample under no applied voltage, respectively, after reconverting their frequency domain back into the wavelength-domain. The previous normalization process can be skipped and replaced instead with a numerical process, in which the original interference spectrum can be separated first into two interference spectra for the ordinary and extraordinary waves by applying the numerical Fourier-transformation and bandpass filtering processes and then each of the separated interference spectra is divided by its envelop spectrum calculated from a Hilbert transformation on it at spectral power level. Most of the noises contained in the interferometer output due to environmental instabilities can be removed during the Fourier transform process. The separated interference spectra can be obtained directly by using a polarized input beam aligned along each of the birefringent axes, but
more careful alignment process is needed. Even in this case a Fourier transform process is needed to eliminate the noises caused by environmental instabilities and to obtain more accurate results. Since the phase difference between two adjacent peaks is $2\pi$, the phase difference spectra are obtained by calculating the phase difference value for $m$th peak with respect to a particular peak at a fixed reference wavelength to be $2m\pi$, and plotted in Fig. 2.2(e) and (f) with open square dots for the ordinary and extraordinary waves, respectively. The above process can be done to obtain the phase difference spectra for the cases without and with an appropriate electric voltage applied to the sample. Then, two plots with closed circular dots in Fig. 2.2 (e) and (f) are obtained for the ordinary and extraordinary waves, respectively, when an electric voltage is applied. Then, the wavelength dependent EO coefficients of the sample can be calculated by using the phase difference values and its known refractive index value $n_0(\lambda)$ at each wavelength in Eq. (2.4).

2.1.3 Results and Discussion

The measured EO coefficients versus wavelengths are plotted in Fig. 2.3. Since a direct current voltage is used in the experiment, the measured phase shift contains the converse piezoelectric effect, and thus the EO values obtained here correspond to the unclamped EO coefficients. The spectral dispersion of the unclamped EO coefficient of the congruent LiNbO$_3$ crystal shown in Fig 2.3 was obtained by applying voltages from 500 V to 800 V with increment of an 100 V interval over a wavelength range from 1450 nm to 1610 nm. Even
though we could get the interference spectrum over a wavelength range from 1430 nm to 1630 nm, its intensity at the both edges of the SOA spectrum was very low, and parts of the wavelength range near the edges were ignored because of significant errors caused by the low intensities. The measurement was repeated 5 times at every applied voltage, and thus the total number of the EO coefficient measurement was 20 times. The averaged values and standard deviations of the EO coefficients were plotted as the center line and error bars, respectively, in Fig. 2.3. The values corresponding to the error bar might be caused by environmental instability of the fiber-type interferometer, which was not fully eliminated during the Fourier transform process, and/or by fitting errors occurred during the numerical processing in relative phase calculation. The refractive indices of the congruent LiNbO$_3$ crystal along the ordinary and
extraordinary axes used during the calculation of the EO coefficient were obtained from the dispersion equation in Ref. 24.

The measured phase difference at 1510 nm wavelength increases with the applied voltage for each of the extraordinary and ordinary waves are shown in Figures. 2.4 (a) and (b), respectively. The results indicate a verified linearity of the measured EO coefficient. The EO coefficients, $r_{33}^T$ and $r_{13}^T$ of the congruent LiNbO$_3$ crystal calculated from the linear curve fitting to the plots in its crystallographic extraordinary and ordinary axes were 28.5 ± 0.15 pm/V and 8.5 ± 0.13 pm/V, respectively. These values are comparable to the effective EO coefficients of a congruent LiNbO$_3$ crystal at 1510 nm wavelength reported in Ref. 8, which included an inverse piezoelectric effect on the conventional unclamped EO coefficients. According to Ref. 8 the IPE effect affects the EO coefficients by amount of about 0.6% and 1.7% for the $r_{33}^E$ and $r_{13}^E$ coefficients, respectively.

The continuous dispersion curves of the linear EO coefficients along the crystallographic extraordinary and ordinary axes of a congruent LiNbO$_3$ crystal have been successfully measured over a wavelength range from 1450 nm to 1610 nm. This method can be extended to measure the continuous dispersion curves of the EO coefficients over a wide wavelength range with a broad white light source.
Figure 2. 4 Phase difference change vs. applied voltage for the (a) extraordinary and (b) ordinary waves in the congruent LiNbO$_3$ crystal
2.2 Nonlinear Coefficient of a highly Nonlinear Optical Fiber

Four-wave mixing (FWM) effect in optical fibers can be applied to quantum information and high-speed signal processing technologies through correlated photon-pair generation, wavelength conversion, and short-pulse generation [25-27]. The efficiency of the FWM effect in an optical fiber is known to be strongly dependent on a power-dependent phase-matched condition which is related to the nonlinear coefficient (NC) and the zero-dispersion wavelength (ZDW) of the fiber [28,29]. Therefore, knowledge of the accurate values of the NC and ZDW is essential to efficient generation of FWM lights. From the 1990s until now, various measurement methods of the NC and ZDW of optical fibers have been reported. Examples of the NC measurement methods are pulsed self-phase modulation method, continuous wave dual-frequency method, modulation instability method, and interferometric method [30-33]. Typical error range of those measurement methods is within 2 to 15%. One of the ZDW measurement methods is frequency-domain phase-shift method [34]. This method has a very small measurement uncertainty of ±0.060 nm, but requires a suitable fitting function for each of different types of fibers. In addition, various FWM signal generation methods have been studied for the NC and ZDW measurements by considering the phase-matched condition between the pump and signal beams [35-39]. Especially, H. Chen proposed a simultaneous measurement method of chromatic dispersion (CD), ZDW and NC with the FWM signal generation [40]. However, this method demands not only accurate
power measurement of the pump and FWM beams but also careful matching of the polarization states of the two pump beams.

In this section, a highly accurate method determining the NC and ZDW of a conventional highly non-linear fiber (HNLF) was described by measuring the pump power dependent optimum pump frequency for peak FWM signal generation conditions. This method provides measurement of the ZDW of the HNLF, at which its chromatic dispersion was completely zero without any influences caused by any external light-beam induced nonlinear effect. Even though the determination of the NC and ZDW of the HNLF with this method is based on the well-known theoretical equations, there has been no report, to our knowledge, related to this proposed method using the pump power dependent optimum pump frequency measurement in determination of the NC of optical fibers so far. The maximum deviations of the measured NC and ZDW values were only within 4.6 % and 0.051 nm, respectively, for four repeated measurements performed at deferent days. We believe that these small measurement errors resulted from the accurate evaluation of the phase-matched condition for the efficient FWM effect. This has been possible with help of fast tuning of tunable lasers used in data measurement and of determination of the phase-matched pump-frequency via curve fitting processes to measured data with computer programs. It is also found that the polarization mismatch is not critical to determination of the NC and ZDW in this method because only relative powers of the FWM generated light were measured.
2.2.1 Theoretical background and Measurement

This method focused on the FWM where two pumps were degenerated. The FWM efficiency $\eta$ is described as [35],

$$
\eta = \frac{\alpha^2}{\alpha^2 + (\Delta \beta)^2} \left[ 1 + \frac{4e^{-\alpha L} \sin^2(\Delta \beta L/2)}{(1 - \exp(-\alpha L))^2} \right] \tag{2.5}
$$

where $\alpha$ is the loss (dB/km) of fiber, $L$ is the fiber length, and $\Delta \beta$ is phase mismatch which is functions of frequency and power of the input pump waves. The power-dependent phase-matching condition, for the maximum efficiency of $\eta = 1$, around the zero-dispersion frequency can be expressed as [28],

$$
\Delta \beta(f, P) = -\frac{2\pi\lambda^4}{c^2} \frac{dD_c}{d\lambda} (f_p - f_s)^2 (f_p - f_0) - \gamma (2P_p - P_s) \frac{1 - \exp(-\alpha L_{eff})}{\alpha L_{eff}} = 0 \tag{2.6}
$$

where $f$ and $P$ are frequency and power of the input beams, respectively, and their subscripts $p$ and $s$ represent the pump and signal, respectively. $f_0$ is the fiber’s zero-dispersion frequency. $D_c$ and $dD_c/d\lambda$ are chromatic dispersion and dispersion slope of the fiber. $\gamma$ and $L_{eff}$ are also the non-linear coefficient and effective length of the fiber. If the frequency difference between the pump and signal waves is kept at a constant value and the pump power is much higher than the signal power (i.e., $P_p \gg P_s$), the equation (2.6) can be written briefly as

$$
f_p(P) = f_0 - \gamma X \cdot P_p \tag{2.7}
$$

where
\[
X = 2 \left[ 1 - \exp(-\alpha L_{\text{eff}}) \right] \left/ \alpha L_{\text{eff}} \right. \left. \frac{2 \pi k^4}{c^2} \frac{dD_c}{d\lambda} (f_p - f_s)^2 \right.
\]

which is valid only within a wavelength range of the linear dispersion slope, i.e., the constant second-order dispersion. Thus, if we measure the pump frequencies \(f_p\) for the phase-matched maximum FWM beam generation condition as a function of the pump power, the non-linear coefficient \(\gamma\) and the zero-dispersion frequency \(f_0\) are simultaneously determined from Eq. (2.7).

Figure 2. Experimental setup for simultaneous measurement of NC and ZDW of a HNLF using the FWM light generation. EDFA: erbium doped fiber amplifier, HNLF: Highly non-linear fiber, PC: polarization controller.
A schematic diagram of the experimental setup used for simultaneous measurement of NC and ZDW with the FWM light generation is shown in Fig. 2.5. Two tunable lasers (TLs; TL 1: HP 8168F, TL 2: Photonetics Tunics-PRI) were used as input pump and signal light sources. The pump light from TL 1 was amplified with a high-power erbium doped fiber amplifier (EDFA; LiComm Co., Ltd.). The pump and signal lights were passed through a polarization controller (PC) and a 90/10 directional coupler with approximately same polarization direction. A little difference of polarization direction did not affect to measured results because only relative power variation of the generated FWM light was considered. 90% of the pump beam and 10% of the signal beam were injected into the conventional HNLF (OFS) of a length of 1.002 km. The injected pump and signal powers were monitored with an optical power meter (EXPO, FRM-300) which was connected to the other port of the directional coupler. The HNLF module was placed in a polystyrene box for isolation from environmental temperature fluctuations, and its temperature was monitored with a negative temperature coefficient (NTC) thermistor (MITSUBISHI, FH05-6D103F*). Power and wavelength of the generated FWM light was measured by an optical spectrum analyzer (OSA; Anritsu MS 9710B). The measured wavelength of the OSA was calibrated by a standard acetylene gas cell ($^{13}$C$_2$H$_2$) which was certified by Korea Research Institute of Standards and Science (KRISS). Figure 2.6 shows a measured example of the spectrum with the input pump and signal lights and the generated FWM light after passing through the HNLF.
Figure 2.7 shows the pump light frequency for the phase-matched condition for the maximum FWM efficiency at a pump power of 12 dBm. Open circles indicate the measured FWM efficiencies as a function of the pump light frequency. Frequencies of the pump and signal lights were simultaneously swept at an interval of 10 GHz, and the difference between the pump and signal frequencies was kept constant at 1,994 GHz (~16 nm). Time spent for each sweep was about 7 minutes. The tuning range of each of the pump and signal frequencies was from 194291.94 GHz (~1543.00 nm) to 194691.94 GHz and from 192297.92 GHz (~1559.00 nm) to 192697.92 GHz, respectively. The wavelength resolution of the TLs was 0.001 nm. The powers of the pump and
signal lights were kept at $12 \pm 0.1 \text{ dBm}$ and $-13.13 \pm 0.02 \text{ dBm}$, respectively. The red solid line is a theoretical fit to the measured data with Eq. (2.7), which shows the peak frequency at 194469.45 GHz.

The parameters used for the theoretical fit were taken from the vendor’s specification for the HNLF. The fiber loss ($\alpha$), length ($L$), and dispersion slope ($dD_c/d\lambda$) of the HNLF were 1 dB/km, 1.002 km, and 0.0207 ps/(nm$^2$km), respectively. Dots are the measured data, and solid lines are linear fits to the data with Eq. (2.7). The y-axis intercepts and slopes of the fitted lines indicate the zero-dispersion frequencies and the nonlinear coefficient of the HNLF, respectively.

Figure 2. 7 Four-wave mixing efficiency of the HNLF as a function of the pump light frequency at a 12 dBm of input pump power: Open circles are the measured data, and solid red line is a theoretical fit.
Figure 2.8 Measured pump light frequencies for the phase-matched maximum FWM light generation efficiency as a function of the input pump light power in four different trial runs.

Figure 2.8 shows the measured pump light frequencies for the phase-matched maximum FWM light generation efficiency as a function of the input pump light power in with a input fixed signal power of -13.1 dBm. The input pump light power was varied from 7 dBm to 12 dBm to avoid the stimulated Brillouin scattering in the HNLF. The temperature of the HNLF was kept at a constant temperature of 20.1 ± 0.03 °C. The data points for one of the linear data fit lines were measured once a day, and thus four sets of the data for the four different lines were taken during 4 different days. The slopes of the linear lines represent the non-linear coefficient $\gamma$ of the HNLF, which turns out to be $11.61 \pm 0.22 \text{ W}^{-1} \text{ km}^{-1}$ according to Eqs. (2.7) and (2.8). This value is similar to that measured
with the CW dual frequency method reported in Ref. 41. The intercepts of the linear data fit lines represent the zero-dispersion frequency $f_0$ which is completely free from any nonlinear refractive-index change, and the ZDW $\lambda_0$ corresponding to the frequency $f_0$ is $1541.47 \pm 0.02$ nm. These values are the mean values of the four trial runs with their standard deviations. We think that those relatively small error values for the mean NC and ZDW resulted from help of a fast tuning capability of the TLs and of determination of the phase-matched pump-frequency via the accurate curve fitting processes to measured data with computer programs.

### 2.2.3 Temperature Dependence of Zero Dispersion Wavelength

Variation of the measured zero-dispersion frequencies from run to run as shown in Fig. 2.8 could not be removed completely because the OSA had a limited wavelength resolution of $0.065$ nm ($\approx 8.1$ GHz). Even though the wavelength reading of the OSA was calibrated with a standard wavelength calibration cell, the accuracy of wavelength measurement with the OSA is limited within the OSA's wavelength resolution. In addition, the laser output wavelength of the TLs has some uncertainty because of the same OSA uncertainty in measuring the laser wavelength. The maximum variation of the measured ZDW was about $0.051$ nm ($\approx 6.42$ GHz) which was similar to the OSA's wavelength resolution.

The deviation of the measured data points from the fitted lines was originated mainly from the environmental temperature fluctuation. We have investigated the temperature dependence of the ZDW measurement as shown in Fig. 2.9.
The open circles and error bars are the mean value and standard deviation of 5 different trial run measurements, respectively. The slope of the line fitted to the data turned out to be 24 pm/°C within a small temperature range between 20°C and 23°C. This temperature dependent ZDW change is very significant in comparison to the phase-matched pump-wavelength variation with the input pump power which is only 4.28 pm/mW as shown in Figure 2.8. Therefore, it can be concluded that the major uncertainty of the measured NC and ZDW values are affected by thermal drift in our system. If the test fiber sample is placed in a temperature controlled chamber, the measurement error can be reduced significantly.

Figure 2.9 Temperature dependence of the measured ZDW of the HNLF for a pump power of 7 dBm. The open circles indicate measured mean value of 5 trial runs, and the red line is a linear fit of the measured data.
Chapter 3. Characteristics and Application of 1.5-μm VCSELs

VCSELs are well known as potentially very useful and low-power consuming optical signal sources for various applications, such as optical communications, optical signal processing, and optical sensing. That is because of their inherent superior characteristics of low power consumption, high-speed modulation with a low driving current, large-scale integration of a two-dimensional array, circular beam output for direct low loss fiber coupling, and low cost packaging capability compared to edge-emitting lasers [42]. Furthermore, the vertically surface emitting geometry and cylindrical symmetry shape of the VCSELs provide many unique characteristics, such as multi-transverse modes, polarization bistability, and polarization switching, compared to the conventional edge-emitting diode lasers. These beneficial characteristics of the VCSELs are potentially very useful for all-optical high-speed two-dimensional signal processing and power-efficient optical communications.

In this chapter I summarize the results obtained with commercially available 1.5-μm wavelength VCSELs provided by Raycan Co., Ltd. for measurement of their polarization bistability as well as timing-jitter-reduced pulse generation and all-optical flip-flop under external laser injection(s). Section 3.1 will introduce the measured results of continuous wave lasing property of a single-longitudinal and transverse-mode (SM) VCSEL. In section 3.2, the timing-jitter-reduced pulse generation of the gain-switched SM VCSEL with an external laser injection will be described. Section 3.3 will explain the observed
polarization bistability property of a single-longitudinal and transverse-mode (SM) VCSEL of conventional circular-symmetric cylinder shape. Experimental demonstration of optical flip-flop operation based on the polarization bistability property of a VCSEL will be discussed in Section 3.4

3.1 Continuous Wave Lasing with 1.5-μm Single Mode VCSELs

The used devices were SM VCSELs of a conventional cylindrical-shape at 1.5-μm wavelength. The VCSELs were all monolithic InAlGaAs/InP laser diodes (LDs) with InAlGaAs/InAlAs distributed Bragg reflectors (DBRs) whose wafer was grown by one-step process of a low-pressure metal-organic chemical vapor deposition (MOCVD) technique [43]. The VCSELs can have fundamental transverse mode lasing output in one of two orthogonal linear polarization states, whose directions are aligned with the <110> and <1̅1̅0> crystal directions of the InAlGaAs/InP compound semiconductor materials, of the fundamental transverse mode. However, if the VCSELs has anisotropic gain or absorption due to asymmetries such as tilted pillar structure, anisotropic transverse cavity, and birefringence then they were expected to deliver laser output at one dominant polarization mode out of two orthogonal polarization modes [44]. Figure 3.1 shows a light-current (L-I) curve of the conventional SM VCSEL with its output powers measured from its pigtailed single-mode fiber (SMF) end at a room temperature. The total output power was linearly increased when its bias current was increased above the threshold current of 2.7 mA. The inset of Fig. 3.1 indicates the measured optical spectrum of the
VCSEL output at a driving current of 7 mA. A few side-mode peaks beside a strong main spectral peak from the single-longitudinal and transverse-mode VCSEL were observed at a wavelength separation of about 0.93 nm and the side mode suppression ratio was larger than 50 dB. The linewidth (full width at half maximum; FWHM) and fiber pigtailed output power of the main peak were about 0.06 nm and 635 µW, respectively.

Figure 3. 1 Measured $L-I$ curve of the conventional single-mode VCSEL. Inset: observed optical spectrum of the VCSEL output at 7 mA.
3.2 Low jittered Gain-switched Pulse Generation

Timing jitter reduction of gain-switched or mode-locked semiconductor laser pulses is very important for application to high-speed all-optical time-division-multiplexing (TDM) communications [45], all-optical signal generation [46] and all-optical clock recovery [47]. Optical injection schemes with incoherent or coherent beams to mode-locked and/or gain-switched semiconductor lasers have been reported previously for time jitter suppression of the laser pulses [48-51].

The injection locked gain-switched semiconductor lasers have many advantages over the mode-locked cases in terms of flexible repetition rate, wavelength selectability and simple configuration. During the last ten years, many researchers have been involved in experimental demonstration and theoretical analysis of jitter reduced pulse sources based on Fabry-Perot (F-P) laser diodes, distributed feedback (DFB) laser diodes and VCSELs with optical injection [52-56]. Previous researches showed a tradeoff relationship between timing jitter reduction and pulse width shortening of laser pulses from external beam injected laser diodes. Especially the low timing jitter signals generated from the VCSELs will be very useful for high-speed long-distance optical communication systems and for single-photon based quantum communication systems [57].

This section was described for the experimental demonstration of simultaneous reduction of the timing jitter and pulse width of optical pulses generated from a 1.5-μm gain-switched VCSEL with an external optical beam.
injection. The root-mean-square (rms) timing jitter, pulse width, pulse amplitude and spectral linewidth measured as functions of the wavelength of the injection laser beam will be described in the following sections.

3.2.1 Experimental Setup

Figure 3.2 shows the experimental setup used for measurement of timing jitter of the gain-switched pulses from a VCSEL by external optical beam injection. A commercially available monolithic 1.5-μm wavelength emitting single longitudinal-mode (SM) VCSEL (Raycan, Korea) was used in this experiment [58]. The VCSEL had active layers of nine 70-Å thick InGaAs quantum wells separated by eight 70-Å thick InAlGaAs barriers and distributed Bragg reflectors (DBRs) of 24 InAlGaAs-InAlAs layers on top and bottom sides. The diameter of the circular aperture of the VCSEL cavity is about 10 μm. The SM fiber pigtailed VCSEL had a threshold current about 2.1 mA at 21.4 °C. The VCSEL’s temperature was kept constant within a temperature variation of ±0.002 °C with a thermo-electric cooler (TEC) packaged in its TO-CAN package under control of a temperature controller. The VCSEL was biased at a driving current of 3 mA, and gain-switched by a 1.25 GHz electrical rectangular pulse stream of a pulse pattern generator (Anritsu MP1632A). The electrical pulse width and peak-to-peak amplitude were 400 ps, and 280 mV, respectively. The VCSEL output power was -9.8 dBm at the bias current of 3 mA in the free-running cw mode. The average power of the gain-switched pulse mode operation was -14.9 dBm without any external beam injection.
Figure 3.2 Experimental scheme for the timing jitter reduction of the gain-switched VCSEL pulses with a tunable laser beam injection
The measured optical spectra of the VCSEL under continuous wave and gain-switched operations are shown in Fig. 3.3 as the solid and dotted lines, respectively. The main spectral and side-mode peaks of the single-longitudinal mode VCSEL output represent two orthogonal polarization modes, and are separated in a wavelength spacing of about 0.34 nm. These two polarization states are originated from the small gain anisotropy due to birefringence and spatial hole burning in the fundamental transverse mode of the circular symmetric structured VCSEL cavity [59-60]. The main spectral peak wavelengths were observed at 1553.86 and 1553.97 nm for each of the CW and gain-switched operation cases, respectively. The corresponding linewidths (full width at half maximum; FWHM) were 0.06 and 0.188 nm. The side mode suppression ratio (SMSR) at the CW operation was about 32 dB, but that at the

Figure 3.3 Measured optical spectra of the VCSEL for a CW mode operation with a bias current of 3 mA and for a gain-switched operation at 1.25 GHz repetition rate.

The measured optical spectra of the VCSEL under continuous wave and gain-switched operations are shown in Fig. 3.3 as the solid and dotted lines, respectively. The main spectral and side-mode peaks of the single-longitudinal mode VCSEL output represent two orthogonal polarization modes, and are separated in a wavelength spacing of about 0.34 nm. These two polarization states are originated from the small gain anisotropy due to birefringence and spatial hole burning in the fundamental transverse mode of the circular symmetric structured VCSEL cavity [59-60]. The main spectral peak wavelengths were observed at 1553.86 and 1553.97 nm for each of the CW and gain-switched operation cases, respectively. The corresponding linewidths (full width at half maximum; FWHM) were 0.06 and 0.188 nm. The side mode suppression ratio (SMSR) at the CW operation was about 32 dB, but that at the
gain-switched operation was only about 15 dB. A tunable laser source (HP 8168F) provided an external CW light injection beam which was coupled via an optical circulator and polarization controller (PC) into the VCSEL. The polarization of the injection light was aligned in the same direction as that of the VCSEL’s main mode, which was easily achieved with a polarization controller. The output from the VCSEL passed through the same optical circulator and then a 50/50 directional coupler. The optical spectrum and the rms timing jitter of the VCSEL output pulses were measured by an optical spectrum analyzer (OSA, Anritsu MS9710A) and a digital communication analyzer (DCA, HP 83485A), respectively.

3.2.2 Results and Discussion

The measured rms timing jitter and spectral linewidth of the gain-switched optical pulses are shown in Fig. 3.4 as functions of the wavelength of the injection beam. The injection power and linewidth (FWHM) of the tunable laser were -23 dBm and 0.06 nm, respectively. The lines connecting the closed circles and the open squares indicate the measured rms timing jitters and spectral linewidths, respectively. The faint gray solid line represents the normalized optical spectrum of the gain-switched VCSEL without any injection in a logarithm amplitude scale. The rms timing jitter which was the standard deviation of the turn-on times of the gain-switched pulses at 50% level of the peak on their rising edge was measured by the DCA. The linewidth of the gain-switched VCSEL under the external laser beam injection became narrow, and
its minimum value was observed when the wavelength of the injection beam was the same with center wavelength of gain-switched VCSEL without injection. The fluctuation of the timing jitter along the injection laser wavelength was observed. The two dips ((c) and (g) points in Fig. 3.4 on the timing jitter curve appeared at the two injection wavelengths, each of which was close to the main spectral peak wavelengths, 1553.86 nm and 1553.97 nm, of the CW operated and gain-switched VCSEL’s spectra without injection, respectively. The timing jitters measured with the laser beam injection at two side wavelengths ((b) and (h) points in Fig. 3.4) of the main spectral mode were larger than that observed without injection. This spectrally fluctuating behavior
of the timing jitter is in a good agreement with the theoretical results expected from Refs. 55 and 56.

The measured pulse shapes and optical spectra of the gain-switched pulses with an external beam injection at several wavelengths are shown in Figs. 3.5(a) to (h). The measured timing jitter value corresponding to the minimum dips of the timing jitter curve of Fig. 3.4 was about 5.5 ps, which amounted to only 40% of the timing jitter of the gain-switched VCSEL’s pulses at the free running mode without injection (Fig. 3.5(c)) and contained the electrical timing jitter of 1.6 ps. The measured linewidth decreased further from 0.188 nm to 0.136 nm as the injection beam wavelength changed from a detuned wavelength far from the main spectral mode to right on the timing jitter dip wavelengths. During the injection beam wavelength change the SMSR of the main spectral mode increased from 15 dB to 31 dB. However, the jitter of the gain-switched VCSEL’s pulses with an optical injection at the center wavelength (1553.92 nm) of their chirped spectrum was observed to be relatively large because two pulses, each with different turn-on times, overlapped together at the same clock time as shown in Figs. 3.5 (d) -(f).

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Figure 3. The measured pulse shapes and optical spectra of the gain-switched pulses with external beam injection of several wavelength
running mode without injection (Fig. 3.5(c)) and contained the electrical timing jitter of 1.6 ps. The measured linewidth decreased further from 0.188 nm to 0.136 nm as the injection beam wavelength changed from a detuned wavelength far from the main spectral mode to right on the timing jitter dip wavelengths. During the injection beam wavelength change the SMSR of the main spectral mode increased from 15 dB to 31 dB. However, the jitter of the gain-switched VCSEL’s pulses with an optical injection at the center wavelength (1553.92 nm) of their chirped spectrum was observed to be relatively large because two pulses, each with different turn-on times, overlapped together at the same clock time as shown in Figs. 3.5 (d) - (f).

The time averaged pulse width and amplitude of the gain-switched VCSEL pulses under the tunable laser beam injection were plotted in Fig. 3.6 as functions of the injection wavelength. The pulse width broadening and amplitude decreasing were observed with the injection beam in a small wavelength detuning range near the center of the main peak mode of the gain-switched VCSEL’s spectrum without injection. These observations behave in a similar way to the experimental results reported with a DFB laser case under an external laser beam injection [52], and to the theoretical results predicted from the VCSELs under injection [56]. However, the previous reports on the injection-induced jitter reduction showed a trade-off relation between low timing jitter and short pulse width.

Contrary to the results of the previous reports we observed the simultaneous pulse width shortening, amplitude increasing, timing jitter reducing and spectral linewidth narrowing of the gain-switched VCSEL pulses with a weak CW laser
beam injection at near the spectral peak wavelength (1553.86 nm) of the free-running VCSEL’s spectrum operating in a CW mode. The conditions are shown in Figs. 3.5(c) and 6 at the dip point of the pulse width curve and at the peak point of the amplitude curve. Possible explanation on these observed results can be described in the following ways. The optimum injection wavelength corresponds to the resonant transition between the spin sublevels of conduction and valence bands [61]. When the injection laser beam wavelength matches this resonant transition’s, it causes a strong induced transition and suppresses all other modes [60]. Thus, the stray signals appearing from all the side modes can be removed, and the signal linewidth narrowing, timing jitter reduction and
pulse width shortening can be obtained as shown in Figs. 3.4 and 3.5(c). Once the pulse width becomes short without any loss of the optical power, it results in enhancement of the peak pulse amplitude.

These simultaneous and adventurous conditions of the gain-switched VCSEL pulses with an external laser beam injection will be very useful in application to long distance high-speed fiber-optic communications. The reduced timing jitter and pulse width of the gain-switched VCSEL pulses lowers error rates in high-speed data transmissions, and the simultaneous reduction in the linewidth will be useful for a long-distance transmission.
3.3 Polarization Bistability of VCSELs

The optical bistability refers to the situation in which two stable optical output states are associated with a given single input state. Several kinds of the optical bistabilities in nonlinear medium and semiconductor laser have been reported which are absorptive bistability, refractive bistability, lasing mode bistability and polarization bistability [62,63]. Theses optical bistabilities can be used for all-optical logic operation and photonic switching.

In this section, we report the first observation of polarization bistability of conventional cylindrical-shaped VCSELs at 1.5-μm wavelength. Conventional VCSELs have fabricated in a circular cylindrical-shaped geometry. Because of the circular symmetric geometry the VCSELs are supposed to deliver a laser output in a random polarization direction whose directions are aligned with the <110> and <1̅10> crystal directions of the InAlGaAs/InP compound semiconductor materials, of the fundamental transverse mode. However, the small gain anisotropy due to an asymmetry resulted from stresses on epitaxial layer growth and on device fabrication as well as birefringent properties on the crystals of the compound materials causes the VCSEL’s laser output at a preferred polarization direction when its driving current is above the threshold and show polarization switching and bistability as the injection current varies. The polarization switching and bistability properties of the VCSELs varied from chip to chip even within one wafer, which might depend on amount of anisotropic stresses built up inside each of the VCSEL chips during the fabrication process.
Figure 3.7 and 3.8 show the measured polarization switching and bistability characteristics of two tested VCSELs. Figure 3.7 shows the polarization-resolved light outputs of one of VCSELs (VCSEL I) versus its bias current by using a fiber-type polarization beam splitter (PBS) to separate the laser output into two polarization outputs. When the driving current was increased, the first lasing mode appeared at an initial polarization state, called as a Y-polarization mode, from the threshold current of 2.7 mA (Fig. 3.7(a)) at room temperature (21°C). The output power of this lasing mode was increased until the driving current was increased up to 5.2 mA, but the lasing mode was suddenly switched to the opposite polarization state, called as an X-polarization mode, at the driving currents above 5.2 mA (Fig. 3.7(b)). The X-polarization mode output was maintained and its output power was increased as the current increased above that. When the driving current was decreased from a high bias current, the X-polarization mode output was maintained until it reached 4.2 mA, and then switched back to the Y-polarization mode output below 4.2 mA.
Figure 3. 7 Measured optical powers of the VCSEL I at (a) Y- and (b) X-polarization mode directions versus its driving current
Figure 3.8 shows the polarization-resolved light outputs in logarithm scale of another VCSEL (VCSEL II) versus its bias current. The VCSEL had a threshold current of 2.4 mA at 17.4 ± 0.002 °C. The VCSEL’s temperature was controlled with a thermo-electric cooler packaged in its TO-can package. Two different polarization switching currents were observed at a 0.5 mA spacing as shown in Fig.3.8. The first lasing mode appeared at an initial polarization state above the threshold current. As the bias current was increased above 4.3 mA, the output switched abruptly to the orthogonal polarization state. On the other hand, as the bias current was decreased from a high current, the polarization mode output was switched back to the orthogonal polarization mode output at 3.8 mA. Insets of Figs. 3.8 (a) and (b) represent optical spectra measured with an optical spectrum analyzer (OSA) at bias current of 4.0 mA as the current was increased and decreased, respectively. The wavelength separation of the spectral peaks between the two orthogonal polarization modes was about 0.04 nm.
Figure 3. 8 Measured L-I curves of the bistable VCSEL II at (a) Y- and (b) X-polarization mode directions. Inset: optical spectra of the VCSEL’s output at 4 mA with (a) increasing bias current and (b) decreasing bias current.
Table 1. Measured polarization switching and bistability characteristics of two tested VCSELs.

<table>
<thead>
<tr>
<th></th>
<th>$I_{th}$</th>
<th>Switching point</th>
<th>Bistable region</th>
<th>$\Delta\lambda$ of bistable modes</th>
<th>Operating temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCSEL I</td>
<td>2.7</td>
<td>5.2, 4.2</td>
<td>1.0</td>
<td>0.09</td>
<td>21 (case)</td>
</tr>
<tr>
<td>VCSEL II</td>
<td>2.4</td>
<td>4.3, 3.8</td>
<td>0.5</td>
<td>0.04</td>
<td>17.4 (chip)</td>
</tr>
</tbody>
</table>

In table 1, the polarization bistability characteristics of two VCSEL samples, fabricated from one same wafer, are summarized. It was observed from our measurements that this polarization bistability property of the VCSEL with change of the driving current varied from chip to chip dependent on the VCSEL chip’s condition such as gain, structure symmetricity, and varying the direction and strength of an applied electric field. Similar behaviors were reported for the 835 nm and 1550 nm bistable VCSELs [64-65].
3.4 All optical Flip-flop Using Polarization Bistable VCSELs

The all-optical flip-flop (AOFF) devices are known to be very important for high-speed optical networks. AOFFs using optical bistable devices can be used for many applications in future high-speed optical networks and optical computing, such as optical switches, optical memories and optical clock generation [66-68]. InP-based semiconductor devices such as semiconductor optical amplifiers, distributed feedback laser diodes, and Fabry-Perot LDs have been used for demonstration of the AOFF [69-71]. An ultimate goal of such devices is demonstration of low power consumption, high-speed operation, and high-density integration for practical system applications. Recently small and low power flip-flop operation of a hybrid InP integrated micro-disk laser on a silicon-on-insulator (SOI) wafer was reported with low electrical bias current and injected switching pulse energy of 3.5 mA and 1.8 fJ, respectively [72]. However, the hybrid integrated device has a significant coupling loss between the InP device, SOI waveguide, and coupled optical fibers. Especially, VCSELs are known to have superior characteristics of low threshold current, low power consumption, low coupling loss to optical fibers, and 2-dimensional array capability compared to the other devices. So, the VCSELs have been recognized as important optical devices for future optical signal processing and optical interconnection applications. In the optical telecom wavelength region of 1550 nm, the AOFF operation based on polarization bistability of a specially designed VCSEL with square-shaped mesa structure was demonstrated, but the
Optical bistability was observed at relatively high-operating current of above 14.1 mA [65].

In this chapter, the demonstration of all-optical flip-flop operation was described using the polarization bistability of the conventional circular cylindrical-shaped 1.5-μm wavelength single-mode VCSEL with a low switching energy of 4.5 fJ.

3.4.1 Experimental Setup

The polarization bistability based all optical flip-flop operations were performed with an experimental setup shown in Fig. 3.9. Modulated signal
pulses from two tunable lasers (TLs) with Mach-Zehnder intensity modulators (IMs) were used for the set and reset optical pulses. The IMs were driven with a 3.2 GHz pulse pattern generator. The set and reset pulses were passed through a 50/50 directional coupler, a variable optical attenuator (VOA) and an optical circulator, and then injected into the VCSEL. The output from the VCSEL passed through the same optical circulator, a 30/70 directional coupler, another polarization controller, and a fiber-type polarization beam splitter (PBS). Two separated orthogonal polarization output from the PBS were measured with a digital communication analyzer (DCA) with two 20 GHz photoreceiver modules.

### 3.4.2 Results

**Low speed AOFF**

At first, a low repetition rate AOFF operation was performed using VCSEL I. The VCSEL was operated at the driving current of 4.7 mA which corresponded to the center of the bistable region. The wavelengths of the set and reset pulses were adjusted to 1552.35 nm and 1552.44 nm by TLs, each of which corresponded to the wavelength of the VCSEL’s Y- and X-polarization mode outputs at 4.7 mA, respectively. The IMs were driven with a delay pulse generator (PG, HP 8130A) at a repetition rate of 25 MHz with 20 ns time delay. The pulse widths of the generated optical set and reset pulses were 1.828 ns and 1.840 ns, respectively. The measured average powers of the set and reset pulse streams were also -17.9 and -16.63 dBm, respectively. The attenuation ratio of
the VOA was set to 15.05 dB, and thus the injected pulse energies of the set and reset pulses into the VCSEL amounted to 10.2 and 13.6 fJ, respectively. Figure 3.10 shows the measured pulse shapes of the injected pulses and the output patterns of the VCSEL under the AOFF operation at a switching frequency of 50 MHz. Initially, the VCSEL output was in the X-polarization polarization direction at the bias current of 4.7 mA with the decreasing current mode as shown in Fig. 3.7 (b). When a set pulse of the Y-polarization direction was injected into the VCSEL, the polarization of the VCSEL output was changed from X- to Y-polarization, and the switched polarization direction was kept holding. Then, as a reset pulse of the X-polarization direction was injected into the VCSEL, its output polarization mode was changed back to the X-
polarization direction. This process is equivalent to a conventional set and reset flip-flop operation. The average contrast ratio between the on and off states of the flip-flop output signals was about 7 dB, which was estimated from the measured signal amplitudes on the DCA. We have experimentally demonstrated the AOFF operation by utilizing the polarization bistability property with low power injection pulses. There are significant rooms for further improvement on the operation speed and switching energy reduction by using a high speed pulse pattern generator and an optimized injection pulse width.

The measured optical spectra of the VCSEL’s output under the AOFF
operation are shown in Fig. 5. The black solid line represents the combined output spectrum of the X- and Y-polarization modes of the VCSEL. The red dotted and blue dashed lines correspond to the optical spectra of the set and reset pulses reflected at the mirror surface of the VCSEL, respectively. These optical spectra also confirm the stable flip-flop operation. The measured wavelength difference of two orthogonal polarization modes of the VCSEL was about 0.09 nm which was less than that of the VCSEL with no polarization bistability reported in ref. 64.

**High speed AOFF**

In the next place, 1-GHz repetition rate AOFF operation was performed using VCSEL II. The VCSEL was operated at a driving current of 4.0 mA which was within the bistable region. The wavelengths of TL 1 (set) and 2 (reset) were adjusted to about 1546.12 and 1546.08 nm, respectively, which corresponded to the peak wavelengths of the X- and Y-polarization outputs. IMs were driven with a 3.2 GHz pulse pattern generator. The pulse widths of the generated optical set and reset pulses were 280 ps and a rising time of 112 ps.

Figure 3.11 shows the measured waveforms of the AOFF operation of the SM VCSEL at a switching frequency of about 1 GHz. The injected pulse energies of the set and reset pulses into the VCSEL were only 4.5 fJ and 3.5 fJ, respectively. These values of the injection pulse energies for the flip-flop operation are less than those reported in Ref. 65.
Figure 3. 12 All-optical flip-flop operation at 1 GHz switching frequency: (a) the set and reset signals injected into the VCSEL and (b) oscilloscope traces of the flip-flop outputs accumulated for an acquisition time of 20 sec

**Measurement of the switch-on and switch off time**

Fig. 3 (a) shows the measured pulse patterns of injected set and reset pulses, each of which had a pulse width of 280 ps and a rising time of 112 ps. When a set pulse stream in the X-polarization direction was injected into the VCSEL, the output was switched from the Y-polarization state to the X-polarization state at a wavelength of 1546.12 nm, and then was kept in the switched X-polarization
state. For injection of the reset pulses in the Y-polarization direction the X-polarization output was returned back to the Y-polarization as shown in Fig. 3(b). Figs. 3 (c) and (d) show the rise and fall times of the switch-on and switch-off transients, respectively. These temporal response times might be reduced further by using injection pulses of short pulse width as shown in Ref. 5. Based on the measured switch-on and switch-off
times our VCSEL can be used for the AOFF operation at frequencies greater than 2 GHz. Further improvement of switching speed of the flop-flop operation can be achieved with high speed pulse generator(s).

The AOFF operation based on polarization bistable VCSEL will be useful for cost-effective and low power consumption applications to high-speed signal processing in future optical switching, optical router, optical memory, and optical computing.
Chapter 4. InGaAs/InP APD based Single Photon Detectors

Single-photon-handling have become very important in quantum communications and quantum information processing [73]. The single photon detector for a 1.5-μm wavelength is a key component in long-distance quantum cryptographic systems because the optical loss of the fiber is the minimum at that wavelength [74]. Over the past 20 years, single-photon detection has progressed rapidly through the use of a variety of techniques using photomultiplier tubes, superconducting Josephson junctions, and avalanche photodiodes (APDs). In this chapter, Characterization of developed SPAD and experimental demonstration of QKD were described.

4.1 Photon Detection with InGaAs/InP SPADs

It is well recognized by many people that InGaAs/InP APDs are potentially useful devices for such application. InGaAs APDs have, however, intrinsically some disadvantages of low quantum efficiency, large dark current, and a high afterpulse effect. In order to overcome these disadvantages, various experimental approaches using a gated Geiger-mode operation with (or without) quenching circuits at cooled low temperatures have been demonstrated for InGaAs APDs. In this section, I describe an experimental demonstration and characterization of an InGaAs APD-based single-photon detector developed for fiber-optic quantum cryptography.
To achieve a low dark count probability, afterpulse suppression, and high quantum efficiency, we used a thermoelectrically cooled InGaAs APD with a gated Geiger-mode operation and passive quenching circuit. The fig. 4.1 and 4.2 shows the schematic diagrams of the Geiger-mode operation method and the electronic circuit used with the SPAD, respectively. An InGaAs/InP APD (JDSU ERM547NT) was operated in a gated Geiger-mode to detect single photons with low dark counts. In the Geiger-mode, a reverse bias voltage exceeding the breakdown voltage is applied to the APD, and a photon impinging on the APD triggers an avalanche process, thus generating a macroscopic current pulse. However, this process also causes a large thermal dark current to flow through the APD and induce an afterpulse effect. The afterpulse effect results from the carriers trapped in the pn junction area during an avalanche. When the trapped carriers are released, they may trigger a new avalanche and cause afterpulses. To reduce the rate of thermally triggered avalanches, we cooled our APD down to −50 °C with a thermoelectric cooler. Since the afterpulse effect becomes significant with increasing macroscopic avalanche current and with increasing excess bias voltage, the macroscopic current must be self-limited to reduce the afterpulse effect. Thus, for this purpose, we used a gated Geiger-mode operation along with a passive quenching circuit that included a large resistor of about 1.1 MΩ connected in series with the APD. When the avalanche takes place, a photocurrent flows through the APD in the circuit. Then, when the gate is switched from open to
Figure 4.2 Schematic diagram of gated Geiger-mode operation for SPAD

Figure 4.2 The electronic circuit of SPAD; $R_1$ (1 MΩ), $R_2$ (100 kΩ), $C_1$, $C_2$ (0.1 μF); passive quenching resistor and decoupling capacitor, $C_3$ (0.1 μF); DC block capacitor, $R_3$, $R_4$, $R_5$ (50Ω); Road resistor, $C_4 = C_{APD}$. 
close, the voltage applied to the APD drops below the breakdown voltage due to the quenching resistor. The bias voltage is kept below the breakdown voltage during the gate-closed state and is raised above it for the Geiger-mode open state only during a time period of $2.4 \sim 4$ ns. Since the total Geiger-mode time is very short, most of the trapped carriers will likely be released between the gate pulses. Thus, this reduces the thermal dark current and suppresses the afterpulses. The electrical pulses produced by the SPAD are reshaped into a few hundred-ns wide TTL pulses by differential amplifier and comparator. This TTL pulses was counted by common frequency counter.

**Photon detection efficiency**

The schematic experimental set-up for measuring the quantum efficiency and the dark count probability of the InGaAs APD is shown in Fig. 4.3. A pulse generator (HP 8131A) triggered with a delay generator (Quantum composers 9500+) was used for gain-switching of the distributed feedback laser diode (DFB-LD). A gain-switched DFB-LD (Avanex A1915LMI) generated short coherent pulses with about 40-ps pulse widths at 1550 nm. These pulses were attenuated to the single-photon level by using a variable attenuator. The output of this attenuator was connected to a pigtailed InGaAs/InP APD (JDSU ERM547NT). The delay generator also triggered another pulse generator (HP 8082A) that provided gate pulses with an amplitude of 5 V and a full width at half maximum of $2.4$ ns. The time delay was set so that the photon impinging on the APD’s sensitive area was synchronized with the gate-on state. Because
of the residual capacitance of the APD, the photodiode was charged (discharged) at every gate-on (off) at which a positive (negative) charge pulse was observed. In the gate-mode operation, the discrimination level was set higher than the charge pulse; therefore, avalanche pulses smaller than the discrimination level could not be counted. For this purpose, we used a parallel load capacitor whose capacitance was equivalent to that of the APD (~3 pF), which was adjusted so that the potential across the two inputs of a differential amplifier connected to the load capacitor and the APD was the same when no avalanche was triggered. On the other hand, when an avalanche was triggered by an impinging photon, a higher current would flow through the APD than through the parallel load capacitor. The amplified avalanche signals from the differential amplifier were transformed into TTL signals with pulse widths of 40

Figure 4.3  Experimental setup for detection efficiency measurement
ns by using a comparator; then the TTL signal was registered at the counter (Stanford research systems SR430).

The detection efficiency $\eta$ was determined by fitting the measured data to the theoretically derived equation [75]

$$P_a = 1 - (1 - P_d)e^{-n\eta}. \quad (4.1)$$

$P_a$ is the probability of avalanche generation per gate pulse, $P_d$ is the dark count probability per gate pulse, $n$ is the average photon number contained in a laser pulse. $P_a$ is simply obtained from the ratio of the count number per unit time measured with a single-photon signal input to the repetition frequency of the gate pulses while $P_d$ is from the ratio of the dark count number per unit time to the repetition frequency. One example of the measured and a fitting curve to eq. 4.1 was shown in Fig. 4.4.

![Figure 4.4](image.png)

**Figure 4.4** One example for measurement of photon detection efficiency
For various bias voltages, we measured the dark count probability and the quantum efficiency of the gated Geiger-mode APD. In Fig. 4.5, the dark count probability per gate pulse is plotted as a function of the quantum efficiency. The points correspond to different excess bias voltages of 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 V, respectively.

A detection efficiency of about 21% was obtained for a dark count probability per 2.4-ns-long gate pulse of $2.6 \times 10^{-5}$ at an operating gate repetition frequency of 10 kHz. The operating frequency can be increased up to 1 MHz with an afterpulse probability below 1% for same detection efficiency.
4.2 Application to Two-way Quantum Key Distribution System.

The QKD technology is known as the ultimate cryptographic technology for future secure communications. Present technologies for QKDs are limited to low key distribution rates and a single transmission line connected directly between two parties. Single photon sources and single photon detectors are most popularly used as quantum signal transmitters and receivers in presently commercialized QKD systems with a protocol called BB84 [76]. The developed SPAD was employed to the two-way QKD which is insensitive to the environmental phase and polarization fluctuations limiting the performance of the one-way scheme [77]. The photon interference was measured in two-way QKD system over the 25-km SMF with developed SPAD.

4.2.1 Experimental Setup

The two-way QKD scheme shown in Fig. 4.2 was formed to measure visibility and quantum bit error rate (QBER) by photon interference. The laser pulses passed through a variable optical attenuator (VOA1) and an optical circulator, and entered into a 50/50 beam coupler (C50/50). Two optical pulses separated by the coupler traveled separate optical paths of an asymmetric Mach-Zehnder interferometer’s two arms, over which the pulse propagation delay difference was about 24 ns, and arrived at a polarization beam splitter (PBS). By adjusting the polarization direction of the two separated pulses to be orthogonal to each other with polarization controllers (PCs), both of the pulses could be combined.
into one, and then exited at one output port of the PBS to enter the single-mode fiber. The pulses that passed through the single-mode fiber proceeded to a 10/90 beam coupler (C_{10/90}) and then to the Faraday mirror (FM). The FM reflected the pulses and rotated their polarization direction by 90°. When the reflected pulses passed through VOA2, their photon numbers were reduced to a single-photon level, and they returned back to the single-mode fiber and to Bob’s side. Since the polarization state of the returning pulses was changed by 90° compared to the incoming state, the returning pulses passed through the opposite side of the PBS and the Mach-Zehnder interferometer, eventually met at the coupler C_{50/50}, and caused an optical interference. The two pulses interfering at the coupler’s output had exactly identical optical paths so that any phase change, polarization fluctuation, and birefringence variation affecting the

Figure 4. 6 Experimental setup for the two-way QKD scheme
pulses were the same, and their effects cancelled out for the interference measurement.

When optical pulses passed through the single-mode fiber, they suffered Rayleigh scattering from the fiber’s inhomogeneity, and some of the scattered photons returned back to the SPAD. These backscattered photons were measured as noise signals. The average power of Bob’s DFB-LD laser pulses was reduced to $-78.6$ dBm ($\sim 110$ photon/pulse) with the attenuator VOA1 to reduce the Rayleigh-backscattering-induced errors. At this pulse power, the Rayleigh backscattering probability was about $3.7 \times 10^{-6}$, which was 10% of the dark count probability. The laser-pulse repetition rate of the DFB-LD was 1 MHz, and the pulse’s wavelength and temporal width were 1554 nm and 50 ps, respectively. The optical path loss of Bob’s side was measured to be 4.1 dB. The output port on Bob’s side was connected to Alice’s side with a 25-km-long single-mode fiber. The round trip loss on Alice’s side was 25.4 dB, and the returning photon number leaving Alice’s side to Bob’s was 0.1 photon/pulse. Synchronization between Alice’s phase modulator and Bob’s pulse generator, phase modulator, and SPAD gates was achieved with a multi-channel electrical delay generator. A LiNBO3 phase modulator PMA ($V_{pi} = 5$ V) was used on Alice’s side to modulate the phase of the delayed pulse, P2, which originated from the pulse splitting at the coupler C50/50 and traveled along the long arm of the Mach-Zehnder interferometer. 5 ns electrical pulses from a pulse generator PG1, which was triggered by the synchronization signal, drove the Alice’s phase modulator. The foregoing optical pulse P1, which was originated from the pulse splitting at the coupler C50/50 and traveled along the short arm of
the Mach-Zehnder interferometer, reflected from the Faraday mirror and returned back to the interferometer by traveling the long arm and by passing through the phase modulator PMB ($V_{pi} = 5$ V). When the pulse P1 passed through the modulator PMB, an electrical pulse of 5 ns in length from the pulse generator PG2 was supplied to the modulator in order to induce a phase change in pulse P1. The two pulses, P1 and P2, arrived at the beam coupler $C_{50/50}$ and proceeded to port A when their phase difference was zero and to port B when the phase difference was $\pi$.

### 4.2.2 Results and Discussion

Figure 4.3 and 4.4 show the measured photon counting at both ports as a result of the dependence of the optical interference on the phase difference.

Figure 4.3 shows the measured photon counts at both port A and port B by inducing the phase changes from $-\pi$ to $+\pi$ with the PMB when its driving voltage was varied from -5 V to +5 V in steps of 1 V while the driving voltage of PMA was fixed at 0 V. The calculated visibility and QBER based on the measured interference curves are summarized in Table 2. The visibility and the QBER were determined by using [78]

$$V = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}}$$

(4.2)

$$QBER = \frac{R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}}$$

(4.3)
Figure 4. 7 Measured photon counts at two output ports of the two-way QKD scheme as the driving voltage of the phase modulator PMB was changed from -5 V to 5V.

Figure 4. 8 Measured QKD photon counts with phase modulation
The measured photon counts at port A during 60 seconds when the phase difference between the phase modulators PM\textsubscript{A} and PM\textsubscript{B} was 0 or $\pi$ are shown in Fig. 4.8. The measured results show that a stable operation of the two-way QKD scheme is possible with random phase changes on the phase modulators on both Alice’s and Bob’s sides according to the BB84 protocol.

The raw key generation rate of QKD systems before an error correction can be expressed as [77]

\[ R_{\text{Raw}} = q \nu \mu \eta \eta_{\text{Bob}} \eta_{\text{det}}, \]

(4.4)

where $q$ is a protocol-dependent constant and corresponds to 1/2 for the BB84 protocol because the probability to use an incorrect basis between Alice and Bob is 1/2. $\nu$ is the repetition rate of the gate pulses driving the laser pulse generation and SPAD gates. $\mu$ is the average photon number per pulse, and $\eta$ is the transmittance of a single-mode fiber. $\eta_{\text{Bob}}$ is the transmittance of Bob’s interferometer, and $\eta_{\text{det}}$ is the quantum efficiency of the SAPD. The quantum key generation rate can be increased by having a high repetition rate for the gate pulses and/or by increasing the quantum efficiency of the SPADs. The results

<table>
<thead>
<tr>
<th></th>
<th>Visibility (%)</th>
<th>QBER (%)</th>
</tr>
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<tbody>
<tr>
<td>Port A</td>
<td>95.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Port B</td>
<td>94.6</td>
<td>2.7</td>
</tr>
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Table 2. Calculated visibility and QBER from the measured interference data of the two-way QKD scheme.
shown in Figure 4.7 were obtained with a quantum key count rate of 2 kHz at port A after a 25-km fiber transmission. The measured results agree well with the calculated values when Eq. 4.4 is used with the experimental parameters $q=1$, $v=1$ MHz, $\mu=0.1$, $\eta_{\text{Bob}}=10^{(-5/10)} \cdot 10^{(-4.1/10)}$, and $\eta_{\text{det}}=0.2$. In this measurement, we could achieve a quantum key generation rate of $R_{\text{Raw}} = 1$ kHz by using the random phase changes on Alice’s and Bob’s phase modulators and by applying the BB84 protocol to the key distribution. It is possible to increase the key generation rate further by increasing the operation speed of the SPAD with an effective afterpulse elimination scheme.

In conclusion, we demonstrated 2-kbit/s quantum interference counts with 1-MHz optical pulses transmitted over a 25-km single-mode fiber in a two-way QKD scheme. The measured QBER was less than 3%. These transmission data enable a 1-kbit/s raw quantum key generation based on the BB84 protocol. A high-speed SPAD with an effective afterpulse elimination scheme should allow a stable high-speed quantum key generation between sender and receiver.
Chapter 5. Summary

In this thesis, I have summarized my works performed during my course of degree program in areas of basic photonic devices related to vertical-cavity surface-emitting lasers (VCSELs) and single-photon detectors for high speed signal processing and quantum communications as well as characterization of nonlinear optical materials for such applications.

New white-light interferometer methods for determination of optical nonlinear properties of optical materials and devices are proposed and proved by using a LiNbO$_3$ crystal and a highly nonlinear fiber, each of which is the typical second- and third-order nonlinear materials, respectively. The white-light interferometer-based second-order nonlinear coefficient measurement method is based on spectral phase changes between an electric field on and off cases to the sample-under-test (SUT), and provides a spectral profile of the electro-optic coefficient of the SUT. A simultaneous measurement of the third-order nonlinear coefficient measurement and zero-dispersion wavelength of a highly nonlinear fiber was performed by scanning the pump beam wavelength to find the pump-power dependent optimum four-wave-mixing signal generation conditions. These methods can be applied for characterization of new nonlinear materials.

Low jittered pulse generation and polarization bistability of 1.5-μm wavelength SM VCSELs have been investigated for potential application to
error-reducing optical pulse sources in quantum communication technologies and to high-speed all-optical signal processing. The timing jitter reduction as well as amplitude increase, and spectral linewidth narrowing of gain switched VCSEL has been demonstrated for the first time to the world under external laser beam injection. In addition, the polarization bistability from a conventional cylindrical-shaped 1.5-µm wavelength VCSELs with change of its operating current has been observed and used for demonstration of 1 GHz all-optical flip-flop operations (AOFFs) with low power injection pulses. Further improvement of the AOFF operation condition can be achieved if a high-speed pulse generator is used. This polarization bistable VCSEL is very useful for cost-effective applications to high-speed all-optical signal processing in future optical network systems.

Finally, I have developed low noise single photon detectors based on InGaAs/InP APDs at 1.5-µm wavelength region, and use them to demonstrate the photon counting capability in a two-way quantum key distribution system.

During the course of this degree program some of technical progresses have made, but there are still significant further works left for the future to have them improved to an elegant state of technology and finally useful in the practical world.
References


