國 立 交 通 大 學
顯示科技研究所
碩士論文

半導體雷射於可調微波光電濾波器與相位偏移器之研究

Tunable Photonic Microwave Filter and phase shifter based on Semiconductor laser

研 究 生: 葉士愷
指導教授: 陳智弘 老師

中華民國九十八年七月

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半導體雷射於可調微波光電濾波器與相位偏移器之研究

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摘要

近幾年慢光效應引起相關研究熱潮，使其在未來全光訊號處理系統中的應用更加廣泛。本論文主旨在研究半導體垂直面射型雷射造成的慢光效應，我們使用射頻單邊帶光訊號，發現其可造成邊帶相位之改變。我們也利用雙邊帶光訊號，結合半導體垂直面射型雷射，進而達成可調式濾波器之效果。我們實際驗證此模組的可行性。而這些研究已進行詳盡的分析與實驗，未來將有助於全光訊號處理系統、相位陣列天線系統以及移動標地偵測雷達系統之發展。

Tunable Photonic Microwave Filter and phase shifter based on Semiconductor laser

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ABSTRACT

In this dissertation, we study slow light in Vertical-Cavity Surface-Emitting Laser. We have experimentally demonstrated the electrical controlled phase shifter based on vertical-cavity surface-emitting laser in a optical single sideband system. The large tunable range with almost 360° phase-shift is achieved by adjusting the bias current of VCSEL. The tunable microwave phase shifter based on VCSEL and SSB modulation has the potential to reduce the size, cost and effectively to overcome the RF fading for microwave systems. Moreover, we also presents a novel tunable microwave filter using slow light in a vertical cavity surface emitting laser. These investigations will be useful in the fields of moving target identification radar systems.

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Chapter 1 Introduction

1-1 Slow Light

Slow light have gained considerable interest with applications ranging from optical communications, optical memories, optical clock distribution, beam steering to RF phased array antenna system [1], and optical signal processing [2]. Slow light has been demonstrated in a variety of systems using approaches based on material or waveguide dispersion [3]. Of particular interest is its application in realizing an all-optical buffer [4][5]. A fixed fiber delay loop or waveguide resonator cannot serve the function of the optical buffer. If the group velocity of light is controllable, a variable time delay is feasible. Additionally, many demonstrations exhibit limited bandwidth not suited to accommodate broadband signals in the high frequency range, as required in many communication applications. This is one main reason why all-optical buffers still do not exist in practice.

Various systems have been demonstrated for slow lights, from electromagnetically induced transparency (EIT) [6], [7], coherent population oscillations (CPO) [8], [9], stimulated Brillouin scattering [10], [11], stimulated Raman scattering (SRS) [12], optical parametric amplification assisted by SRS [13], four-wave mixing (FWM) [14] ~ [18], etc. Tunable delay using semiconductor devices attracts much attention because it offers the advantages of compactness, room temperature operation, and easy integration with existing optical communication systems. Slow light can be obtained by introducing a change in the absorption (or gain) spectrum of semiconductor quantum well and quantum dots . Although EIT in semiconductor QDs has been proposed for slow light [19], [20] most recent experiments have been successful using CPO or FWM in QW and QD devices from low to room temperatures. For example, the absorption (or gain) spectrum can be changed via CPO [21], [22], [23], depletion of the exciton absorption peak [24], or wave mixing in a semiconductor WG absorber [25]. In addition, both slow and fast light at room temperature can arise from a change in a sharp gain spectrum [26][27][28][29].

1-2 Vertical-Cavity Surface-Emitting Laser (VCSEL)

VCSEL is a kind of semiconductor laser. The light beam of laser propagates normal to the epitaxial layers. The VCSEL require 99% mirror reflectivity (or much better) to balance the short axial length of the gain region. Growing Distributed Bragg Reflectors (DBRs) can achieve such high reflectivity and consist of alternating quarter-wavelength layers of semiconductor material with different refractive index. The DBRs are parallel to the wafer surface. In common VCSELs the upper and lower mirrors are doped as p-type and n-type materials, forming a diode junction. In more complex structures, the p-type and n-type regions may be buried between the mirrors, requiring a more complex semiconductor process to make electrical contact to the active region, but eliminating electrical power loss in the DBR structure. The small active volume of VCSEL permits to achieve low threshold current together with high modulation bandwidth.

There are several advantages to producing VCSELs when compared with the production process of edge-emitting lasers. Edge-emitters cannot be tested until the end of the production process. VCSELs however, can be tested at several stages throughout the process to check for material quality and processing issues. VCSEL also provide significant benefits in terms of manufacturability and costs. The fabrication limited to wafer-scale steps allows processing monolithic arrays. Their circular output beam and low divergence simplifies fiber coupling and make VCSEL convenient for cheap packaging in array configurations.

Longer wavelength devices, from 1300 nm to 2000 nm, have been demonstrated with at least the active region made of indium phosphide. VCSELs at even higher wavelengths are experimental and usually optically pumped. 1310 nm VCSELs are desirable as the dispersion of silica-based optical fiber is minimal in this wavelength range.

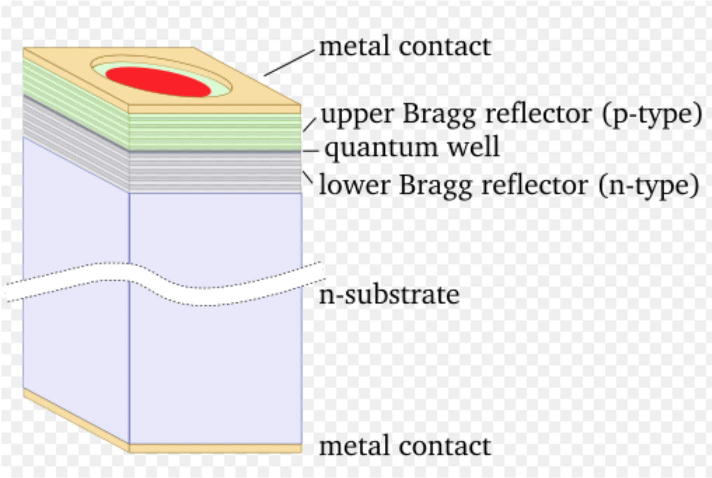

Fig. 1-1 Diagram of simple VCSEL

1-3 Motivation

Slow light has many application such as optical communications, optical memories, optical clock distribution, RF phased array antenna system, and optical signal processing. Over the past years, there are some method to slow down the signal. Make the signal go the long way (e.g. Fiber delay line), mike the signal go slower through dispersive medium (e.g. Coherent population oscillation), and make the signal bounce around by introducing reflections in its path (e.g. cavity, gratings).

However, there may be another method to build up a tunable delay/advanced system which is much cheaper, simpler, lighter, and easier to control than previous research. In addition, there may be other applications in slow/fast light. We want to build up a tunable delay system which can have potential to be used in a real system. We finally decided to use semiconductor devices (VCSEL) to proceed our experiment.

We expected the system can have more advantages such as good compactness, and it is easy to integrating with existing optical communication system.

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Chapter 2 Phase Shift in VCSEL

2-1Introduction

This investigation experimentally demonstrates the tunable phase shifter based on a semiconductor laser in single side-band systems at 10 GHz. The simulation shows good agreement with the experimental result.

Slow light devices (Optical delay lines) are important components in optical communication, signal processing, and phase-array antenna systems [1][2]. The optical delay lines using semiconductor-based devices are very attractive due to inherent compactness, directly electrical controllability, and low power consumption [3][4][5][6]. Moreover, slow light at room temperature in a quantum dot semiconductor amplifier has been recently demonstrated because quantum dots can provide better carrier confinement, reduced thermal ionization, and carrier escape at room temperature [7][8]. In addition, semiconductor lasers with the quantum dot gain medium also have been studied to improve the laser characteristics, including low threshold currents, temperature insensitive, low chirp, and high differential gain [9]. Recently, there has been significant progress in the development of monolithically single-mode vertical-cavity surface-emitting lasers (VCSELs) [10].

Recently, there has been a strong and growing interest in applying the photonic technology to radio frequency (RF) phase shifter for phased array antennas. The advantage of photonic RF phase shifter is immunity to electromagnetic interference, excellent isolation, and potential benefits of light weight and small size [11]. In this chapter, we report the slow light in the monolithically single-mode VCSEL for the photonic RF phase shifter at 10 GHz. The monolithically single-mode VCSEL has the potential to reduce the size and cost of the RF phase shifter for microwave photonic systems.

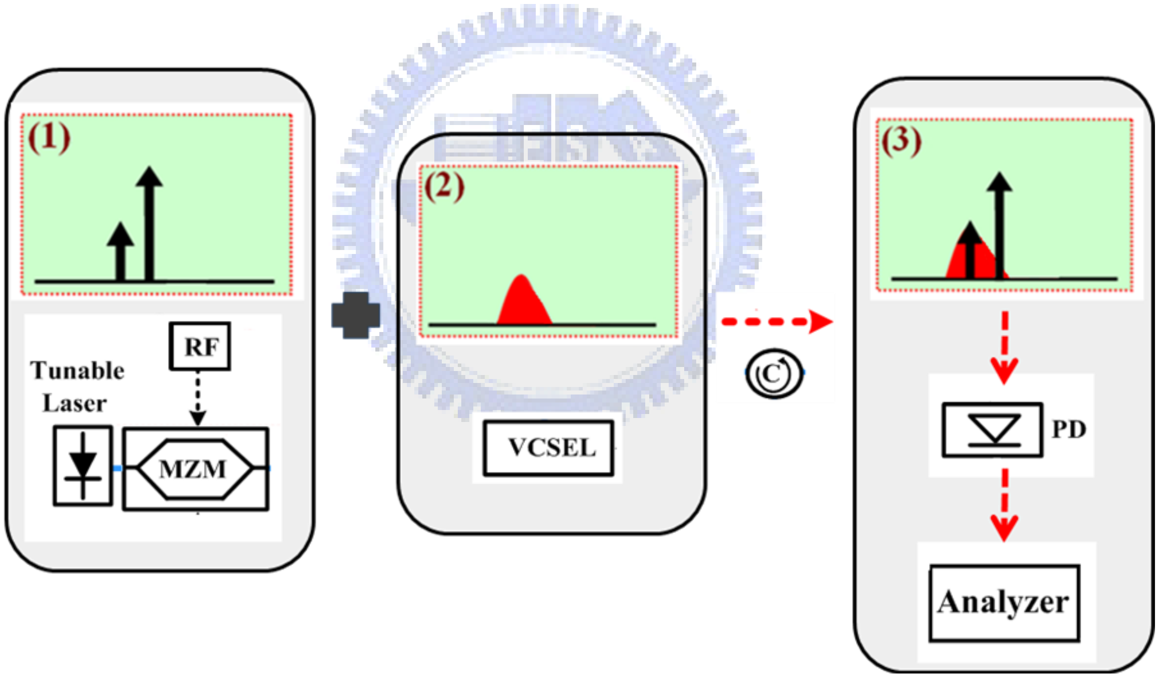

Fig. 2-1.The flow path of experiment and simulation. (MZM: Mach-Zehnder Modulator, C: optical circulator, PD: photodetector)

2-2 Theory and Experimental

The flow path for measuring the microwave phase shifter in the optical single sideband system (left sideband) is schematically depicted in Fig.2-1. The probe signal is generated by a laser source and modulated to an optical single sideband signal. The output light from the VCSEL and probe signal is guided through the optical circulator. Then, the optical signal is sent to analyzer. Finally, we can get the phase change response.

The phase change response is Fig. 2-2.

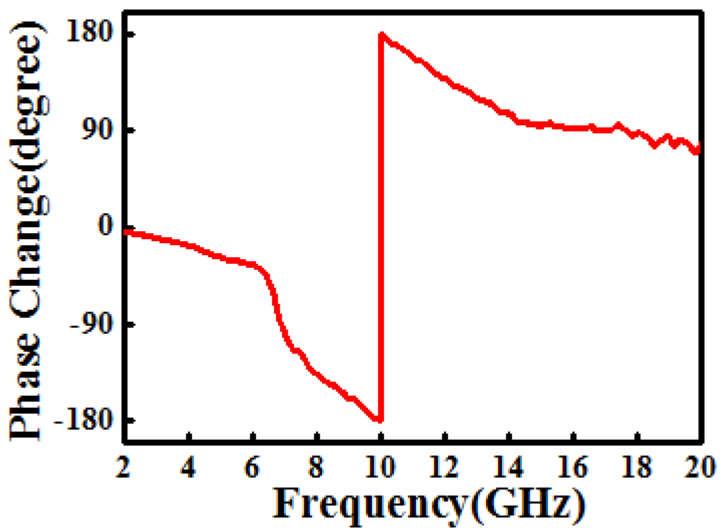

Fig. 2-2.The phase change response.

We used a Fabry-Perot analysis[12]. GD is calculated by (2.1)

$$GD(\lambda) = \frac{2L_c}{c} \frac{R_b g_s^{\,2}(D^2 - R_f^{\,2}) - \sqrt{R_f R_b}(1 + R_b D g_s^{\,2})(D - R_f) * g_s * \cos 2\phi}{R_f + R_b g_s^{\,2}(D^2 + R_f^{\,2} + R_f R_b D^2 g_s^{\,2}) - 2\sqrt{R_f R_b}(1 + R_b D g_s^{\,2}) g_s (D + R_f) \cos 2\phi + 4 R_f R_b D g_s^{\,2} \cos^2 2\phi} \tag{2.1}$$

We consider gain effect of GD. The detuning wavelength (λ detuning) induce gain effect which leads to change in the single pass gain(gs) and coupled intensity(Po). Following ref.[13], g_s experienced by gain effect can be expressed as (2.2)

$$g_s = g(N)[1 - \frac{C_p P_0 (T(\lambda)/T(0))[1 + P_0(T(\lambda)/T(0)) + \frac{\beta * c * \tau_s}{\lambda_{\det uning}}]}{(1 + P_0(T(\lambda)/T(0)))^2 + (\frac{\beta * c * \tau_s}{\lambda_{\det uning}})^2}]$$

(2.2)

The ratio(T(λ)) of the input power to the coupled intensity in VCSEL is given by (2.3)

$$T(\lambda) = \frac{(1 - R_f)}{(1 - \sqrt{R_f R_b})^2 + 4\sqrt{R_f R_b}\sin^2(2\pi L_c / \lambda + \lambda_{\det uning})}$$

(2.3)

(R_f R_b : front and back DBR intensity reflectivity g_s : single-pass gain Lc : optical length of cavity C_M : coupling factor between incident wave and cavity mode D : C_M-$C_M R_f$+R_f)

The sketch of simulation and result is shown in Fig. 2-3.

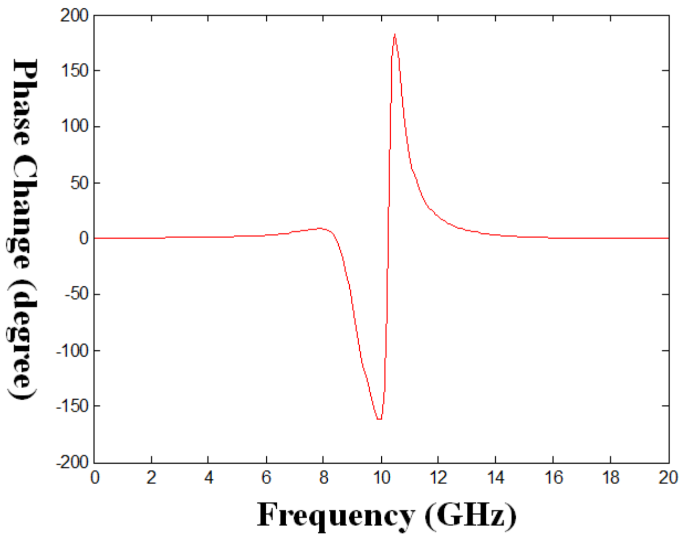

Fig. 2-3.The phase change charge of simulation.

The simulation shows good agreement with experimental result.

2-3 Conclusion

We experimentally demonstrate slow light in a VCSEL at room temperature for photonic RF phase shifter. The RF phase shifts with the frequency 10 GHz are achieved. Moreover, the simulation also shows good agreement with experimental result. The photonic RF phase shifter with total phase shift of nearly 2π. The slow light in the VCSEL has the potential to be used in RF phase shifter for phased array antennas.

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Chapter 3 Electrical Controlled Phase Shifter using Semiconductor laser in Optical Single Sideband Systems

3-1Introduction

This investigation experimentally demonstrates the electrical controlled phase shifter based on a semiconductor laser in single side-band systems. The operational bandwidth from 12 to 20 GHz is achieved by adjusting the bias current.

In recent years, microwave photonic devices have attracted much attention because of their many advantages such as immunity to electromagnetic interference, wide bandwidth, excellent isolation, small size and low weight [1-3]. One of the key devices in microwave systems is phase shifters. Recently, photonic microwave phase shifters have been reported [2-3]. Moreover, we also experimentally explored a tunable optical delay based on the quantum dot vertical-cavity surface-emitting laser (VCSEL) [4]. However, the electrical controlled phase shifter based on a VCSEL in single sideband systems has not yet been elucidated.

Optical single sideband modulation techniques can eliminate completely the effects of fiber chromatic dispersion in radio over fiber system [5-6]. In this paper, we experimentally explore a VCSEL for a microwave phase shifter in an optical single sideband modulation system. The operational frequency from 12 to 20 GHz with full

360° phase shift is achieved by adjusting the bias current of VCSEL. This investigation will be useful in the field of radio over fiber systems.

3-2 **Experiments and Results**

The experimental setup for measuring the microwave phase shifter in the optical single sideband system is schematically depicted in Fig.3-1. The probe signal is generated by a laser source and modulated to an optical single sideband signal. The optical single sideband modulator is based on a dual-drive Mach-Zehnder modulator with a 90°-hybrid coupler. The Output spectrum of single sideband signal is shown in fig.3-2. The wavelength of probe signal is fixed at 1542.79 nm. The probe signal is injected into a VCSEL via an optical circulator (C). Fig. 3-3 shows the optical spectra of VCSEL at various current. Fig. 3-3 shows the optical spectra of VCSEL at various current. The polarization controller (PC) is used to adjust the polarization of probe signal. The output light from the VCSEL is guided through the optical circulator. Than, the optical signal is split by 1×2 optical coupler, one is sent to optical spectrum analyzer, another is sent to photodetector. Finally, the amplitude and phase change response are measured by a network analyzer. In the experiment, the power of probe signal is kept constant while the bias current of VCSEL is varied. Fig. 3-4 (a), (b), (c), (d), and (e) show the amplitude and phase change response of the QD VCSEL at various bias currents of VCSEL. The bias current of VCSEL in Fig. 3-4 (a), (b), (c), (d), and (e) are 1.23mA, 1.33mA, 1.40mA, 1.48mA, and 1.56mA, respectively. When the bias current of VCSEL is changing from 1.23mA to 1.56mA, the phase change is moving from 12 GHz to 20GHz.

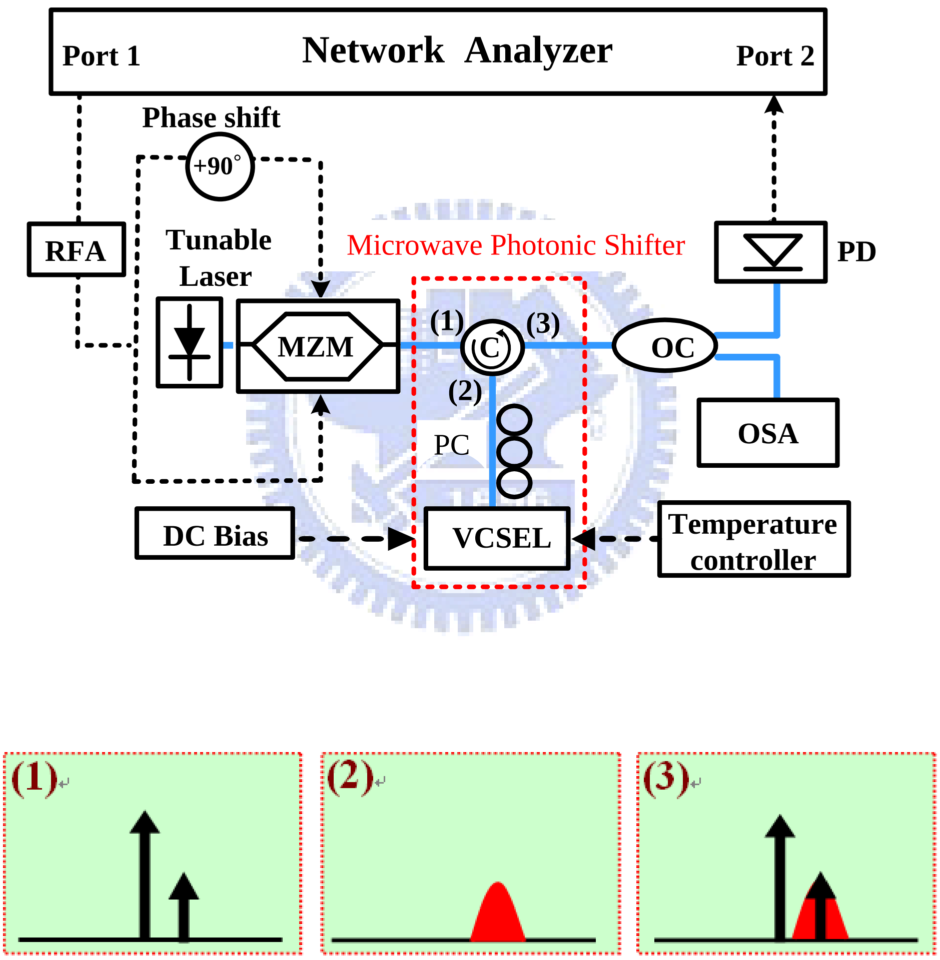


Fig. 3-1. Experimental setup for measuring the microwave phase shifter in the optical single sideband system. (MZM: Mach-Zehnder Modulator, C: optical circulator, OC: optical coupler, PC: polarization controller, RFA: RF amplifier, PD: photodetector, OSA: optical spectrum analyzer)

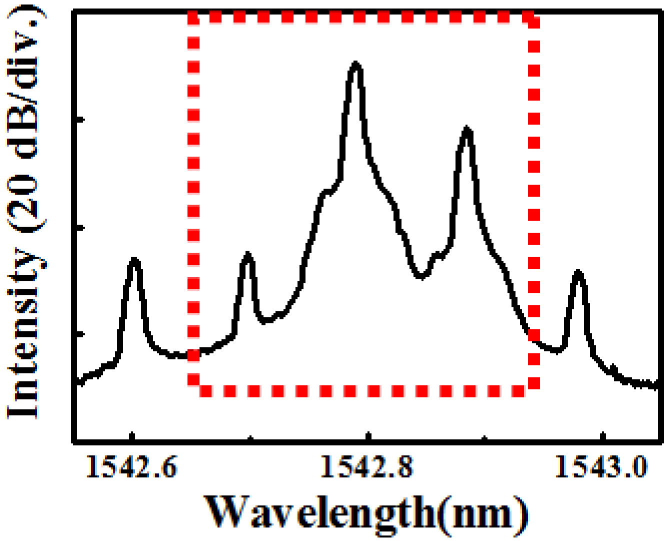


Fig. 3-2. Output spectrum of single sideband signal.

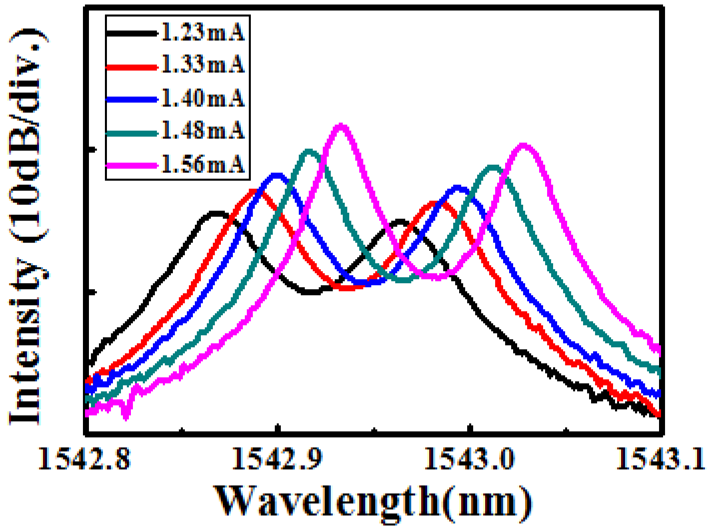
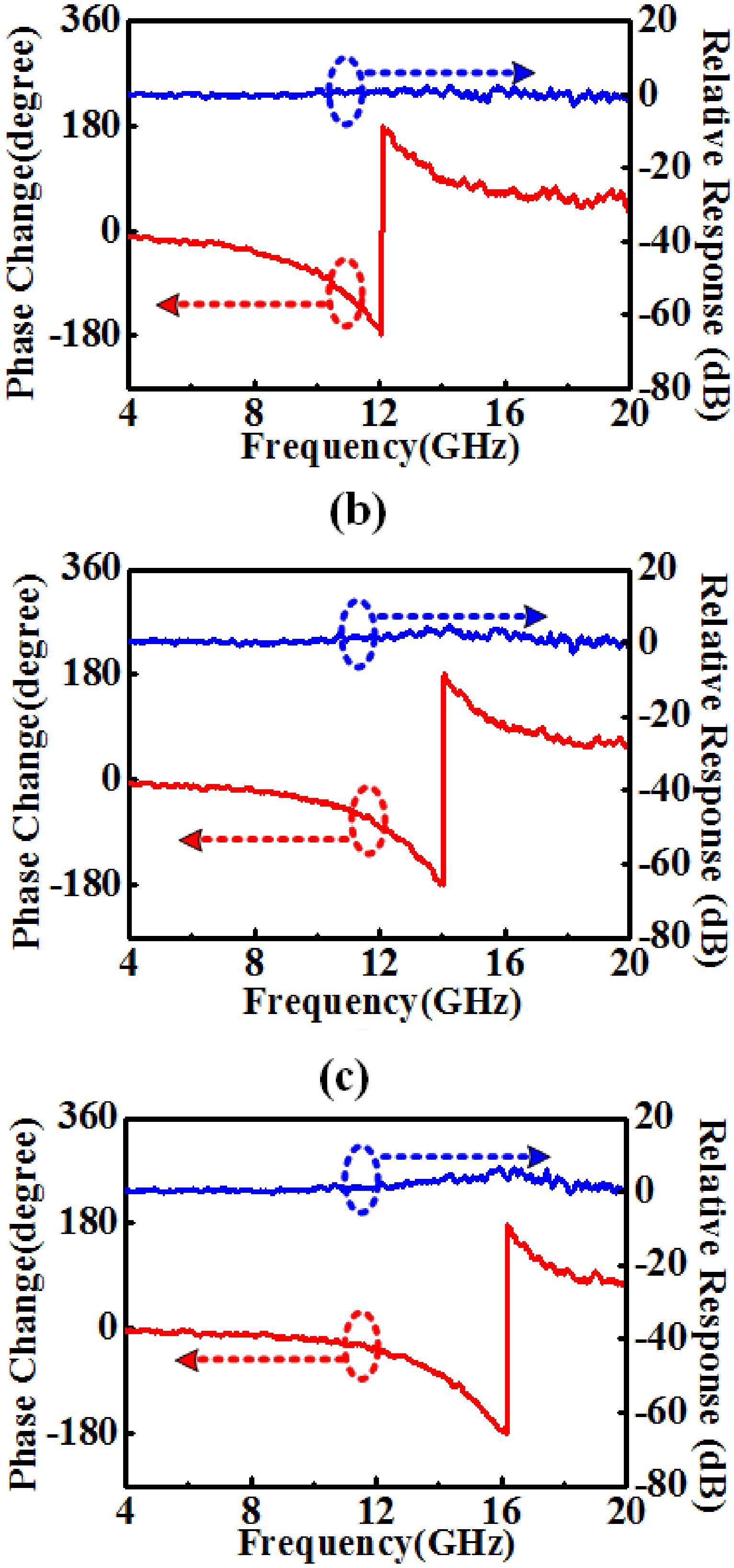


Fig. 3-3. Output spectra of VCSEL at the various bias currents.

(a)

(b)

(c)



Phase Change(degree)
360
180
0
-180
Relative Response (dB)
20
0
-20
-40
-60
-80
4
8
12
16
20
Frequency(GHz)

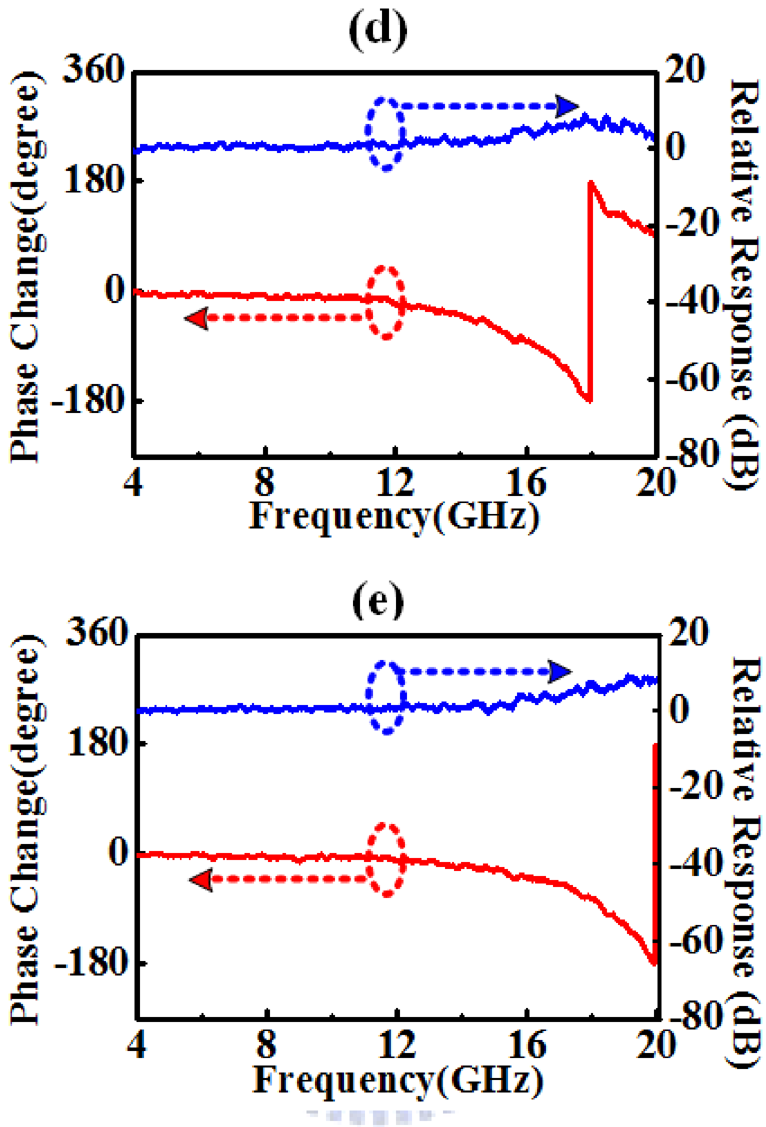


Fig. 3-4. Amplitude and phase change response at bias current of (a)1.23mA, (b)1.33mA, (c)1.40mA,(d)1.48mAand (e)1.56mA, respectively.

3-3 Principle

When the modulator is biased at the quadrature point (when the driving voltage is set at Vπ/2), the modulated signal is a kind of double sideband (DSB). The electrical field at the output of the modulator is given by (3.1) [7](with the expansion in Bessel functions)

$$\begin{aligned}E &= E_0\cos(b)J_0(m)\cos(\omega_0 t)\\ &+E_0\sin(b)J_1(m)\cos[(\omega_0+\omega_{RF})t]\\ &+E_0\sin(b)J_1(m)\cos[(\omega_0-\omega_{RF})t]\end{aligned} \tag{3.1}$$

where

$$m=\frac{V_{RF}}{2V_\pi}\pi \quad , \quad b=\frac{V_{bias}}{2V_\pi}\pi$$

In this experiment, the modulated signal is single sideband(SSB). The electrical field at the output of the modulator is given by (3.2)

$$\begin{aligned}E &= E_0\cos(b)J_0(m)\cos(\omega_0 t)\\ &+E_0\sin(b)J_1(m)\cos[(\omega_0-\omega_{RF})t]\end{aligned} \tag{3.2}$$

After the VCSEL inject into the right sideband, the phase of the right sideband will be changed. The electrical field at the output of the modulator is given by (3.3)

$$\begin{aligned}E &= E_0\cos(b)J_0(m)\cos(\omega_0 t)\\ &+E_0\sin(b)J_1(m)\cos[(\omega_0-\omega_{RF})t+\theta]\end{aligned} \tag{3.3}$$

After square-law detection , we get the photo current term (3.4)

$$I = \frac{1}{2} J_0^{\,2}(m)\cos^2(\omega_0 t)$$
$$+\frac{1}{2} J_1^{\,2}(m)\cos^2[(\omega_0 - \omega_{RF})t + \theta]$$
$$+J_0(m)J_1(m)\cos(\omega_0 t)\cos[(\omega_0 - \omega_{RF})t + \theta]$$

(3.4)

3-4 Conclusion

In this paper, we have experimentally demonstrated the electrical controlled phase shifter based on vertical-cavity surface-emitting laser in a optical single sideband system. The tunable range from 12 to 20 GHz with almost 360° phase-shift is achieved by adjusting the bias current of VCSEL. The tunable microwave phase shifter based on VCSEL and SSB modulation has the potential to reduce the size, cost and effectively to overcome the RF fading for microwave systems. Finally, we have studied the tunable microwave phase shifter which is almost 360° RF phase shift and is operated over a broadband bandwidth. It has potentially useful to achieve tunable RF delay as well as optical delay in all optical processes.

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Chapter 4 Tunable Photonic Microwave Filter using Slow Light in VCSEL

4-1Introduction

"Slow light" has attracted a lot of interest because it can find some applications such as optical signal processing, optical buffers, optical communication, optical data synchronization, optical memories, radar, and phase-array antenna systems [1-2]. In recent years, slow light have been experimentally demonstrated in coherent population oscillations, electromagnetically induced transparency, and stimulated Raman and Brillouin scattering [2]. The slow light devices based on semiconductor devices are very attractive because of low power consumption and compactness [3]. Recently, tunable slow light in vertical-cavity surface-emitting lasers (VCSEL) also have been reported [4-5].

There are many previous tunable microwave photonic filter researches [8-12]. However, tunable slow light in a VCSEL for a tunable microwave filter has not yet been addressed. These are some advantages such as large tuning range, simple setup, low cost and directly electrically current controllable.

The microwave phonic filter is a kind of all-optical filter which is different from traditional RF circuit filter.[7] When it is applied in radar and photonic beamsteering of phase-arrayed antennas. (Fig 4-1)It is required after signal detection, and carry out the filtering of all the noise from the target. In order to distinguish the small echo from the target and the large echo from the fixed objects, high-performance digital-analog convertion are required. It is also a huge disadventage in the phase-arrayed antennas system. If all the noise can be removed before down-conversion (Fig. 4-2), we do not have to use the high-resolution digital-analog convertion. However, the tuning range of traditional RC circuit tunable photonic filter is not large enough for moving target radar system [7]. To remove the noise and clutter before down-conversion, the highest notch position must reach higher frequency. These reason explain why making a tunable microwave photonic filter is worthy. There are some previous research result [8][9]. There are a lot of modulators, gratings, and tunable lasers which make their setup heavy and expensive. Their tuning range is less than 3 GHz, and first notch can just reach 8.5 GHz. We wonder whether we can break these limits, and we also want to built up a much cheaper, simpler, and electric current controllable tunable microwave photonic notch filter.

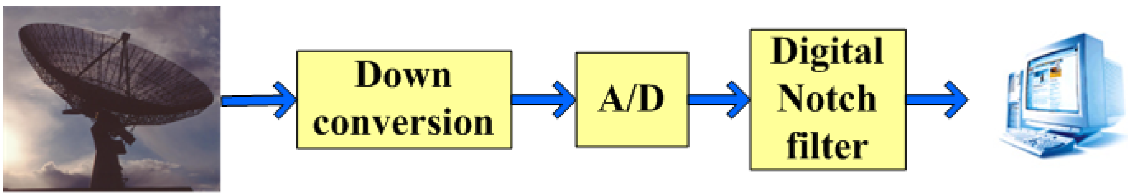

Fig. 4-1 Typical signal processing configuration in a MTI radar system

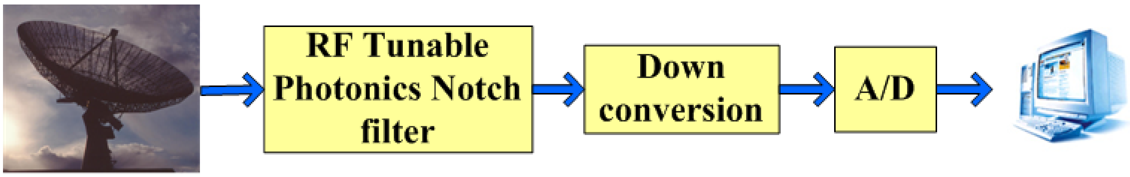

Fig. 4-2 Modified version including a microwave photonic filter prior to down-conversion

4-2 **Experiments and Results**

A tunable photonic microwave filter using slow light in a VCSEL is proposed and experimentally demonstrated for the first time. Tunable microwave notch filter at 20 GHz can be achieved by adjusting the bias current of VCSEL. We propose a novel photonic microwave notch filter which is highly tunable and electric current controllable. By changing the electric current of VCSEL, notch frequency can be varied continuously keeping its free spectral range. The tuning range have been improved and the setup is much simpler and cheaper than previous research result.

Figure 4-3 shows the experimental setup for measuring the tunable photonic microwave filter. A probe signal is generated by a laser source and then modulated via an electro-optical modulator (EOM). The wavelength of probe signal is 1542.785 nm. The electro-optical modulator is modulated by a network analyzer (HP 8720ES). The RF signal is produced by Network analyzer, and it is form 0.5GHz to 20GHz. the laser is modulated by a subcarrier signal. When the modulator is biased at the quadrature point, in other words, the middle transmission point. The generated optical signal is double sideband (DSB). An optical circulator (C) is used to couple the probe signal into the VCSEL. The polarization of the probe signal is adjusted by a polarization controller (PC). Then the output signal from the port 3 of the circulator is split into two paths, sent to an optical spectrum analyzer (OSA) and a photodetector (PD), respectively. Finally, the amplitude and phase changes are measured by the network analyzer.

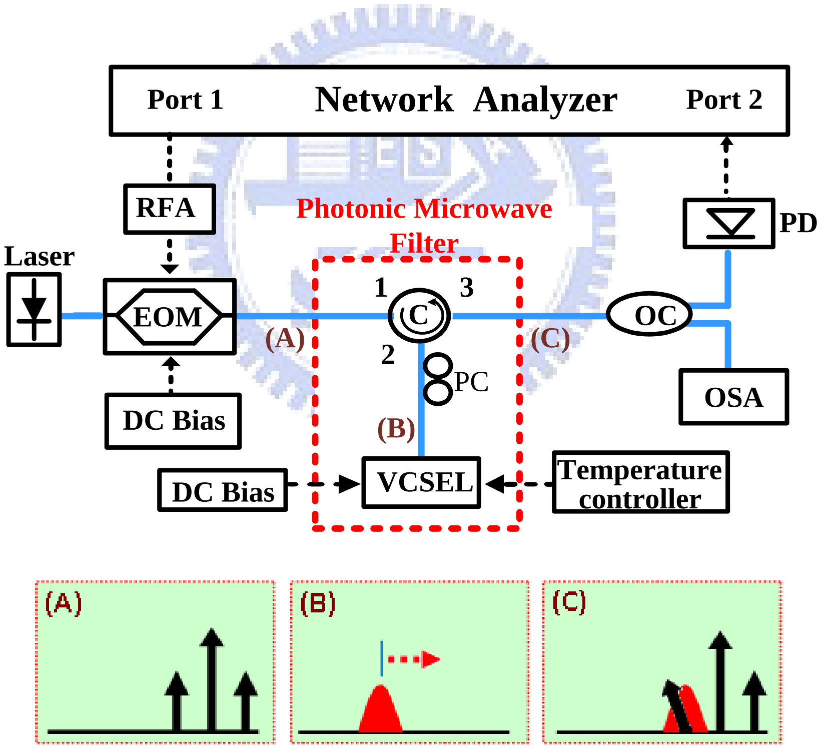

Fig. 4-3 Experimental setup of the proposed photonic microwave filter. (EOM: electro-optic modulator, C: optical circulator, OC: optical coupler, PC: polarization controller, RFA: RF amplifier, PD: photodetector, OSA: optical spectrum analyzer)

Figure 4-4 shows the light-current characteristics and figure 4-5 shows the output spectrum of the VCSEL. Figure 4-4 is the relationship of VSCEL between the current and power. Figure 4-5 is the relationship of VSCEL between wavelength and power. When the current increase, the wavelength and power of VSCEL pump laser will increase.

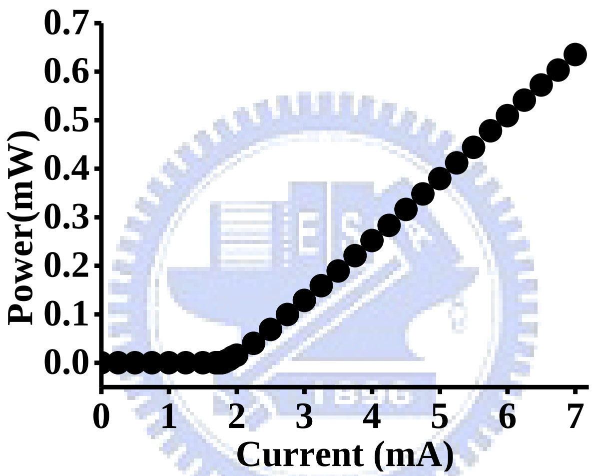

Fig. 4-4 Light-current characteristics

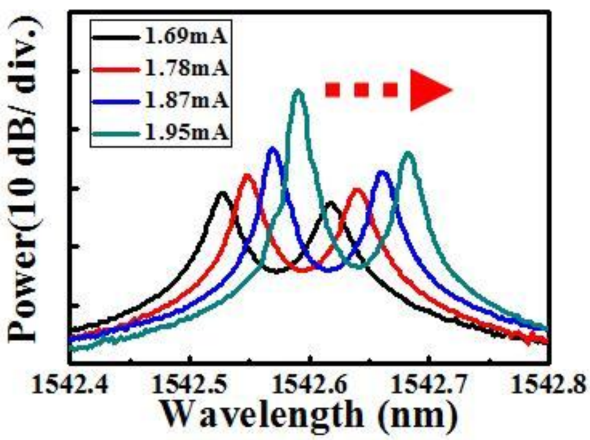

Fig. 4-5 Output spectrum of the VCSEL

In the experiment, the power of input probe signal is kept constant while the bias current of VCSE is varied. Fig. 4-6 shows the amplitude at the various bias currents of VCSEL, respectively. When the bias current changes from 1.90 mA to 1.69 mA, the notch moves from 13.37 GHz to 20 GHz. The tunability of the microwave photonic filter can be achieved to nearly 7 GHz. When the current of VSCEL is increasing, the notch will be shifted to the lower frequency. The highest measurement frequency of 20 GHz is limited by the network analyzer (maximum measurement frequency). Decreasing the bias currents of VCSEL can increase the central frequency of the microwave filter. The highest rejection level reached is over 36 dB. Figure 4-7 shows the relation between VCSEL bias and notch position, and it is nearly a linear relation. On the other hand, it is also desirable that the tunable photonic microwave notch filters are electric current controllable.

The phase change also can be tuned by adjusting the bias current of VCSEL (Fig.4-8). The phase change of 2π is observed. The amplitude response rapidly decreases as the phase change increase. And the free spectrum range (FSR) is more than 10GHz, there is only one notch in the frequency response.

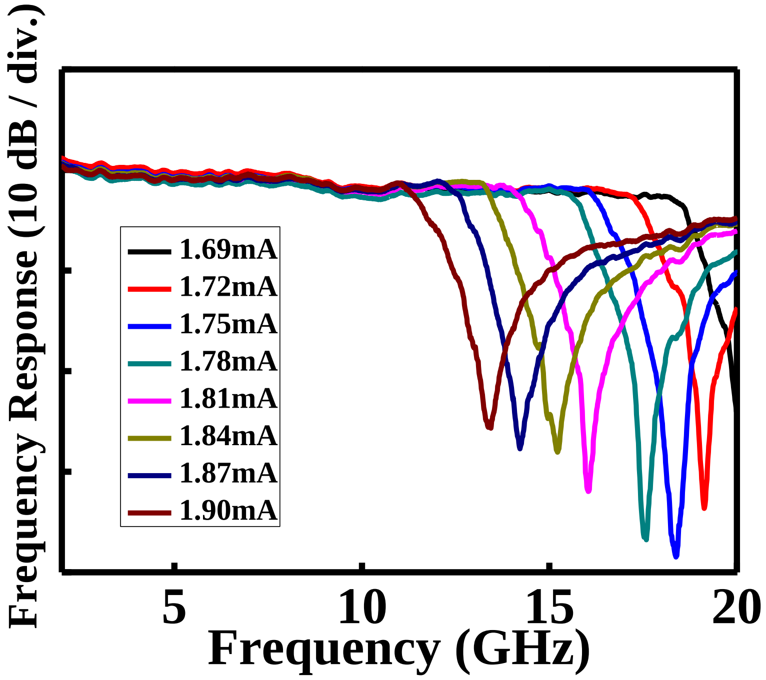

Fig. 4-6 Amplitude response of proposed microwave filter at various bias currents.

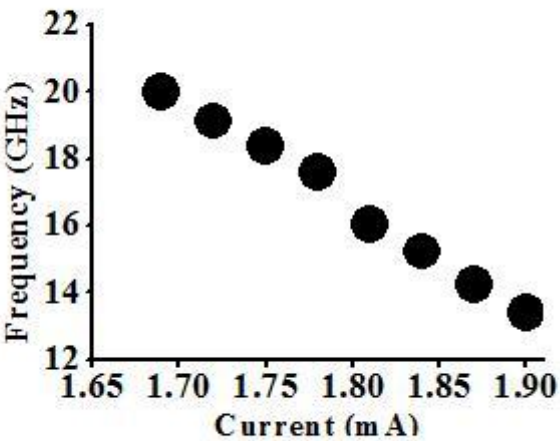

Fig. 4-7 The relation between VCSEL bias and notch position.

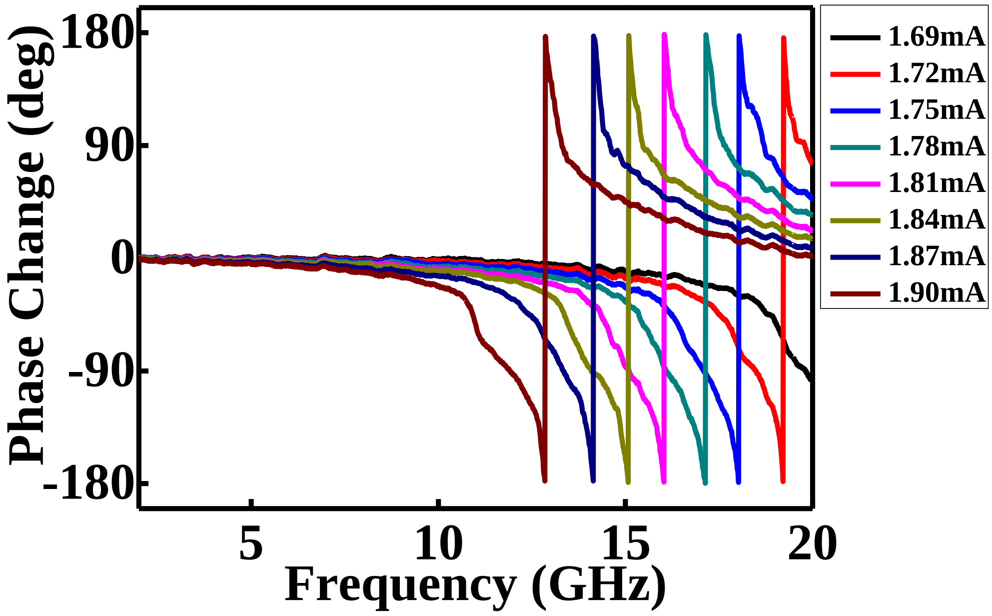

Fig. 4-8 Phase change response of proposed microwave filter at the various bias currents.

Figure 4-9 shows the frequency response when the notch is at 16GHz, and two below picture shows the optical spectrum. The left picture is the optical spectrum when the radio frequency is 5 GHz. The VSCEL does not injected into the lift sideband yet. The right picture is the optical spectrum when the radio frequency is 16 GHz. The amplitude and phase of the lift sideband is changed. The notch is at 16GHz, the phase change is equal to pi at 16 GHz. From the optical spectrum, the sideband is moving from center carrier to outside according to the frequency of RF signal. Obviously, the injection between VSCEL and the left sideband occur at 16 GHz.

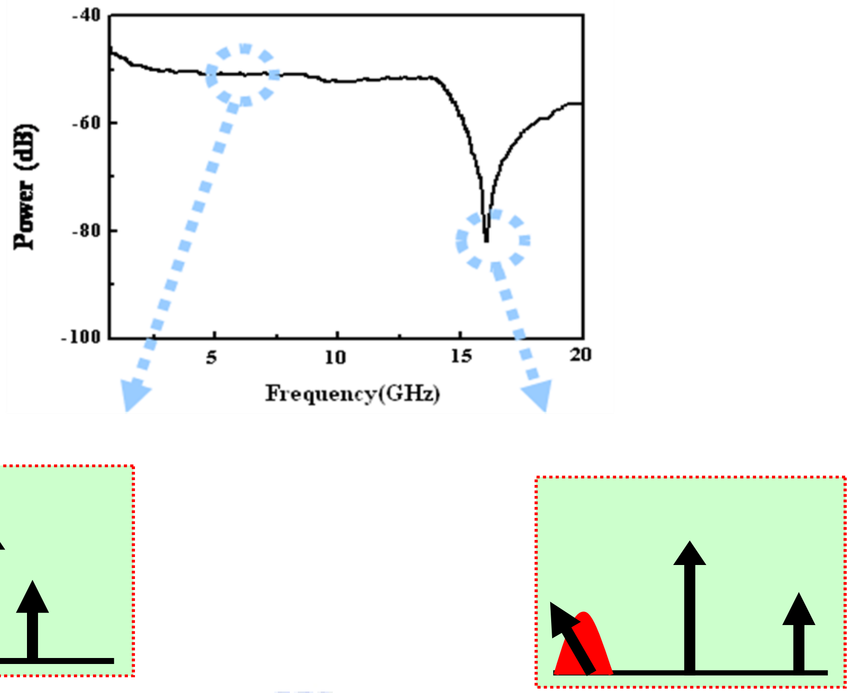

Fig. 4-9 Frequency response when the notch is at 16GHz. VCSEL inject into the left sideband.

4-3 Principle

When the modulator is biased at the quadrature point (when the driving voltage is set at Vπ/2), the modulated signal is a kind of double sideband (DSB)[Fig. 4-3(A)]. The electrical field at the output of the modulator is given by (4.1) [13](with the expansion in Bessel functions)

$$\begin{aligned} E = {} & E_0 \cos(b) J_0(m) \cos(\omega_0 t) \\ & + E_0 \sin(b) J_1(m) \cos[(\omega_0 + \omega_{RF})t] \\ & + E_0 \sin(b) J_1(m) \cos[(\omega_0 - \omega_{RF})t] \end{aligned} \tag{4.1}$$

where

$$m = \frac{V_{RF}}{2V_\pi}\pi \quad , \quad b = \frac{V_{bias}}{2V_\pi}\pi$$

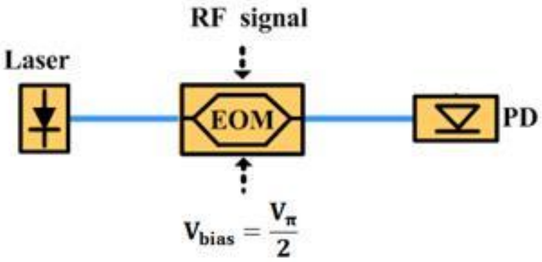

Fig. 4-10 Modulator is biased at quadrature point.

When the current of the VCSEL is increasing, the wavelength of VSCEL will increase. From the optical spectrum analyzer, we can see that the wave of VSCEL will move to the right side. After VSCEL injecting to the left sideband, the phase of the left sideband will be changed [12]. So there is a phase change term Θ which is added into the left sideband term, given by (4.2) [Fig. 4-3(C)]

$$\begin{aligned} E = {} & E_0 \cos(b) J_0(m) \cos(\omega_0 t) \\ & + E_0 \sin(b) J_1(m) \cos[(\omega_0 + \omega_{RF})t + \theta] \\ & + E_0 \sin(b) J_1(m) \cos[(\omega_0 - \omega_{RF})t] \end{aligned} \tag{4.2}$$

After square-law detection , we get the photo current term (4.3)

$$
\begin{aligned}
I = &\frac{1}{2}J_0{}^2(m)\cos^2(\omega_0 t) \\
&+\frac{1}{2}J_1{}^2(m)\cos^2[(\omega_0+\omega_{RF})t+\theta] \\
&+\frac{1}{2}J_1{}^2(m)\cos^2[(\omega_0-\omega_{RF})t] \\
&+J_0(m)J_1(m)\cos(\omega_0 t)\cos[(\omega_0+\omega_{RF})t+\theta] \\
&+J_0(m)J_1(m)\cos(\omega_0 t)\cos[(\omega_0-\omega_{RF})t] \\
&+J_0{}^2\cos[(\omega_0+\omega_{RF})t+\theta]\cos[(\omega_0-\omega_{RF})t]
\end{aligned}
\tag{4.3}
$$

Because the network ananyzer could not read the THz term, these terms are supposed to be deleted. In the end, we get the truly photo current term, given by (4.4)

$$
\begin{aligned}
I = &\frac{1}{2}J_0(m)J_1(m)\cos(\omega_{RF}t+\theta) \\
&+\frac{1}{2}J_0(m)J_1(m)\cos(\omega_{RF}t)
\end{aligned}
\tag{4.4}
$$

And we find out that when Θ is equal to pi, the current is equal to zero. It is the minimum value. This is the reason why there is a notch in the frequency response.

4-4 Conclusion

Compare with previous result [8][9][10][11], we propose a novel photonic microwave notch filter which is highly tunable and electrical current controllable. In our research, there are just one modulator and VCSEL system in the tunable microwave photonic filter. The tuning range has been improved and the setup is much simpler and cheaper than previous research result. Tunable photonic microwave filters have recently attracted considerable interest because they allow the processing of microwave signal in the optical domain with advantageous features such as, low loss, wide bandwidth, and immunity to electromagnetic interference [6-7]. One application is the tunable notch filter which can be used for wireless communication systems and radar applications. In this paper, we report slow light in a VCSEL for a tunable microwave notch filter. The operation frequency is from 13.37 GHz to 20 GHz, and the highest rejection level reached is over 25 dB. The proposed system has the potential to reduce the size and cost of the microwave filter for microwave photonic systems.

In summary, we presents a novel tunable microwave filter using slow light in a vertical cavity surface emitting laser. The tunable range from 13.37 to 20 GHz has been experimentally demonstrated by varying the bias current of VCSEL. The highest rejection level greater than 36 dB was observed. Moreover, we also study the relationship between the phase change response and the bias current of VCSEL. The slow light in the VCSEL has the potential to reduce the size and cost of the microwave filter for microwave photonic systems. And if we use the advanced network analyzer and photodetector, we are supposed to have the ability to built up a 60GHz microwave photonic notch filter. It is much cheaper than other research. There are many advantages which is invincible all over the world, such as low cost, large tunability, easy to control, light weight.

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Chapter 5 Summary

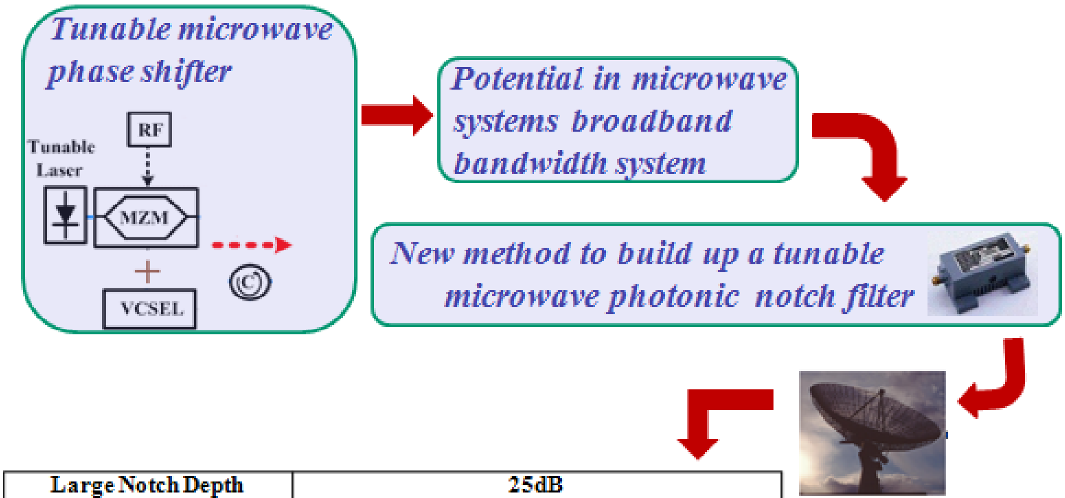
5-1 Conclusion

We experimentally demonstrate slow light in a vertical-cavity surface-emitting laser at room temperature for photonic RF phase shifter. The RF phase shifts with the frequency from 12 to 20 GHz are achieved by varying the VCSEL current. The tunable microwave phase shifter based on VCSEL and SSB modulation has the potential to reduce the size, cost and effectively to overcome the RF fading for microwave systems. Moreover, we also study the relationship between the amplitude change response and the wavelength detuning. The photonic RF phase shifter with total phase shift of 2π with about 8 GHz bandwidth has been demonstrated. The slow light in the VCSEL has the potential to reduce the size and cost of the RF phase shifter for phased array antennas and all optical processes.

We also propose a novel photonic microwave notch filter which is highly tunable and electrical current controllable. The tuning range has been improved and the setup is much simpler and cheaper than previous research result. Tunable photonic microwave filters allow the processing of microwave signal in the optical domain with advantageous features such as, low loss, wide bandwidth, and immunity to electromagnetic interference. One application is the tunable notch filter which can be used for wireless communication systems and radar applications. We report slow light in a VCSEL for a tunable microwave notch filter. The operation frequency is from 13.37 GHz to 20 GHz, and the highest rejection level reached is over 25 dB. The highest rejection level greater than 36 dB was observed. Moreover, we also study the relationship between the phase change response and the bias current of VCSEL.

5-2 Future Work

If we use the advanced modulator, network analyzer, and photodetector, we are supposed to have the ability to built up a 60GHz microwave photonic notch filter which can have potential to used in 60GHz optical communication system.



Large Notch Depth	25dB
Electric Current Controllable	VCSEL current from 1.90mA to 1.69mA
Large Tuning Range	6.63GHz
Inexpensive & Simple	One VCSEL & One Modulator

Fig. 5-1 Flow chart of the experiment.