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고밀도 파장분할다중 네트워크 응용을 위한 Quaternary InGaAsP 다중양자우물 QCSE 다중 채널원

(Quaternary InGaAsP MQW QCSE Tuned Multichannel Source for DWDM Networks)

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요 약

본 논문은 고밀도 파장분할다중 (DWDM) 시스템의 응용을 위하여 quaternary/quaternary 다중양자우물 InGaAsP/InGaAsP QCSE 튜닝을 이용한 1550 nm 다중 채널원에 관한 것이다. 본 채널 소스는 140 GHz 채널 간격을 갖으며 32 nm 채널 선택 대역을 갖는다.

Abstract

This paper describes a 1550 nm multichannel source using quaternary/quaternary multiple quantum well (MQW) InGaAsP/InGaAsP quantum confined Stark effect (QCSE) tuning for dense wavelength division multiplex (DWDM) systems with 140 GHz channel spacing and 32 nm channel selection bandwidth.

Keywords : QCSE, MQW, InGaAsP, DWDM

I. Introduction

In this paper, a 1550 nm multichannel source using quaternary InGaAsP MQW QCSE tuning for DWDM systems with 140 GHz channel spacing and 32 nm channel selection bandwidth will be described.

In future DWDM systems multichannel 1550 nm tunable sources are required to reduce inventory and costs. Most tunable semiconductor lasers have used carrier injection effect (CIE) tuning[1]. Because the forward bias modulation carried out using electro-absorption modulators, the interaction between red-shifting thermal effects and blue-shifting carrier density effects leads to a non-uniform tuning response with significant device to device variation. However, the QCSE modulation achieved using reverse bias tuning resulting in no thermal effects and carrier induced nonlinear effects. The QCSE gives an uniform and reproducible tuning response and is therefore of considerable interest as a tuning as well as channel selection mechanism. In earlier work an 850 nm wavelength QCSE tunable laser using the

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GaAs/AlGaAs material system was reported[2][3][4][5][6]. Although QCSE in the InGaAsP/InP material system has been studied extensively[7][8][9][10], 1550 nm InGaAsP MQW QCSE tuned lasers have not been demonstrated so far.

II. Structure of InGaAsP/InP MQW Tuning Element

The DWDM source comprises an external cavity with a gain laser and a quaternary InGaAsP multiple quantum well PIN reflective tuning element. The QCSE tuning element is an InGaAsP/InP PIN structure with a distributed Bragg reflector (DBR) mirror as shown in Figure 1. The contact layer is an InP layer and an intrinsic InP spacer is used between the InP contact layer and the MQW layers. The MQW system consists of 60 10 nm-thick Q1.6 wells and 61 7.5 nm-thick Q1.1 barriers. Beneath the MQW layers a 16-layer Q1.4 InGaAsP/InP DBR is positioned with designed quarter wavelength thickness at 1550 nm and 80% reflectivity. To reduce parasitic series resistance the DBR stack was n-doped. All layers were growth on an n^+ InP substrate by conventional atmospheric pressure metal-organic vapour phase epitaxy (MOVPE). The tuning elements were fabricated using standard photolithography, thermal evaporation and wet chemical etching. A single layer anti-reflection coating of Si_3N_4 was deposited by plasma enhanced chemical vapour deposition (PECVD) on the p^+ InP surface to reduce reflection from this interface. Mesa etching was used to form 400 μm-diameter devices. Completed devices were coupled to the rear facet of the gain laser using an anti-reflection coated GRIN lens. A coupled cavity was established between the rear facet of the gain laser and the DBR stack of the tuning element.

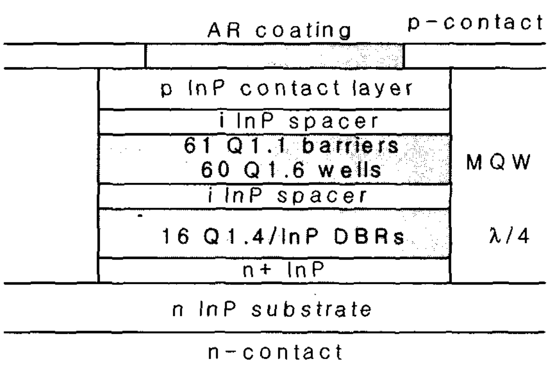

그림 1. InGaAsP MQW PIN 소자 구조
Fig. 1. Structure of the InGaAsP MQW PIN device.

III. Experimental Arrangement of the MQW QCSE Multichannel Source

As shown in Figure 2 the front facet of the laser was coupled via a collimating lens, isolator and a focusing lens to the measurement system comprising an optical spectrum analyzer, an optical frequency discriminator and an heterodyne detection system with tunable external cavity laser and lightwave signal analyzer. The DWDM source comprises an external cavity with a gain laser and a large area PIN quaternary InGaAsP MQW tuning element. Using an anti-reflection coated GRIN rod lens the light output of the gain laser is collimated and focused to the DBR in the QCSE modulator.

To optimize the experimental arrangement the center wavelength should be at the wavelength where the MQW material provides maximum refractive index change and minimum absorption change. The rough alignment relied on choosing a suitable gain laser and MQW dimensions.

Fine adjustment was by optimizing the laser injection current, MQW bias variation range and the temperature of gain laser. Because the tuning range is proportional to $1/L$, where L is the cavity length,

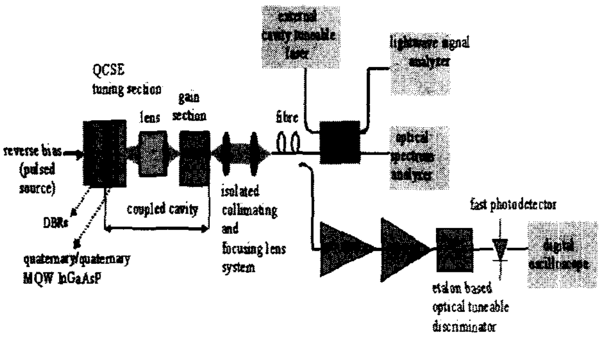

그림 2. MQW QCSE 다중채널원의 실험 구도
Fig. 2. Experimental arrangement of the MQW QCSE multichannel source.

the external cavity should be as short as possible to utilize the limited refractive index variation in MQW device and achieve large tuning range. Optical and mechanical stability is required. First, the position of the tuning element was adjusted by measuring the photocurrent of the device. Next, the position was set to be close to a multiple of the gain laser's cavity length to get the maximum mode selection sensitivity by testing the maximum power output of the external cavity laser. The gain laser was an InGaAsP/InP Fabry-Perot MQW laser without anti-reflection coatings having a centre emission wavelength of 1565 nm at room temperature. The threshold current of the gain laser was about 8 mA. At the threshold current the center wavelength is 1565 nm at room temperature, which is 18 °C. A Peltier thermal pump and temperature controller was used to adjust the laser diode temperature from 5 °C to 50 °C. Apart from injection current, this gave an additional means to align the laser emission at the optimized MQW wavelength.

A coupled cavity was established between the rear facet of the gain laser and the DBR stack of the tuning element. The system can be analyzed as a multiple cavity system with emission occurring at the wavelength where the two cavity resonances coincide. Because the coupling of the external cavity to the laser diode is less than 10 % of the output optical power of the gain laser, its main effect is to select laser internal cavity modes[11]. Figure 3 shows the L-I characteristics of the InGaAsP MQW laser with QCSE tuning element. The slope efficiency is changed due to the weak feedback effect. The threshold current, which is 8 mA, and the gain charactertics is shown in Figure 4.

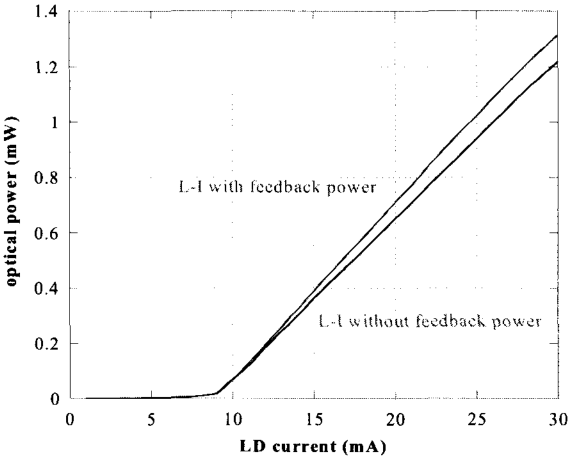

그림 3. QCSE 튜닝부가 있는 InGaAsP MQW 레이저의 L-I 특성

Fig. 3. L-I characteristics of the InGaAsP MQW laser with the external QCSE tuning element

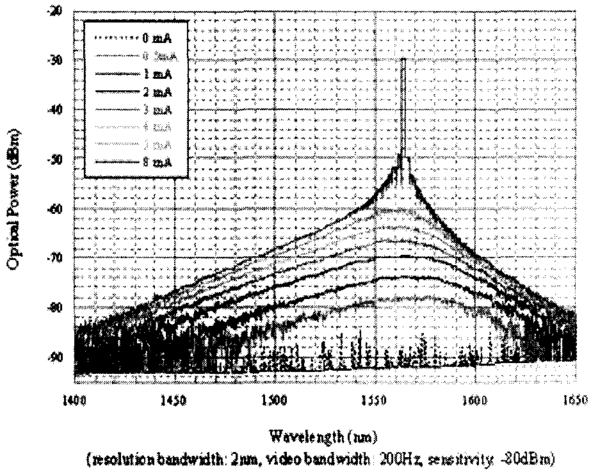

그림 4. InGaAsP MQW 레이저의 tm펙트럼 특성

Fig. 4. Spectral characteristics of the InGaAsP MQW laser

Ⅳ. Measurement of the Static Characteristics of InGaAsP/InP MQW QCSE

The results were observed by using the measurement system of Figure 2. The system includes an optical spectrum analyzer, scanning Fabry-Perot analyzer and a heterodyne system including a coupler and an external cavity laser source as a local oscillator. The light emerging from both output arms of this coupler, when detected, exhibits an intensity fluctuation, or modulation, at a rate equal to the frequency difference between the two input lasers. For a 100 % beam-combining efficiency in the heterodyne modulation scheme, the magnitude of the modulated optical power equals the sum of the average power and the modulated power:

$$p(t)=\frac{1}{2}(p_{avg1}+p_{avg2})+(P_{avg1}\cdot P_{avg2})^{\frac{1}{2}}\cdot \cos[2\pi(f_2-f_1)t] \quad (1)$$

where p_{avg1} and p_{avg2} are average optical powers of the first input and the second input respectively, and f is its frequency. If the average power of each laser were known, this method provides a known amount of modulated optical power at the difference frequency, f_2-f_1. In this coupled cavity QCSE tuned system internal laser cavity modes can be selected by tuning the fundamental external cavity mode to a subharmonic of the internal cavity mode.

Optimum tuning sensitivity occurs when l_l , which is the length of the external cavity, is close to an integral multiple of l_o, which is the minimum value being set by the onset of multiple operation. Δl , which is the optical path length of external coupled cavity laser, can be determined from the optical frequency shift Δf produced by tuning the external cavity[2]. Continuous static tuning measurements using the heterodyne measurement system gave a frequency change, $\Delta f=0.8\,GHz$ for a reverse bias change of 0 to 10 V corresponding to $\Delta l \cong 43nm$. $\lambda_0=1560nm$, which is the center wavelength, $l_l=14.5mm$ and d_{MQW}, which is the total thickness of MQW intrinsic layer, is 1.372 μm. The refractive index change, which can be calculated by $\Delta n=\Delta L/d_{MQW}$, is 4.3732×10^{-2}. Therefore, for a device with intrinsic region thickness 1.372 μm this gives 1.25 % refractive index change at a wavelength 20 nm below the exciton absorption peak which is in good agreement with other work[2][5][7].

The maximum continuous tuning range is 1.2 GHz when the reverse bias applied from 0 V to 16 V is applied as shown in Figure 5.

Without AR coating on the facets of the gain laser the continuous tuning is limited by the laser internal modes. When the reflection coefficient is zero, the interface vanishes and continuous tuning can be achieved without accompanying output power change. The continuous tuning range largely depends on the optical length of the external cavity and the change in length achieved. The operating wavelength is tuned by changing the temperature of the gain laser. At each operating wavelength the QCSE frequency shift is measured by applying the same electric field. The peak of the refractive index change which is close to the exciton peak is at 1550 nm wavelength and the frequency shift is 250 MHz at this wavelength.

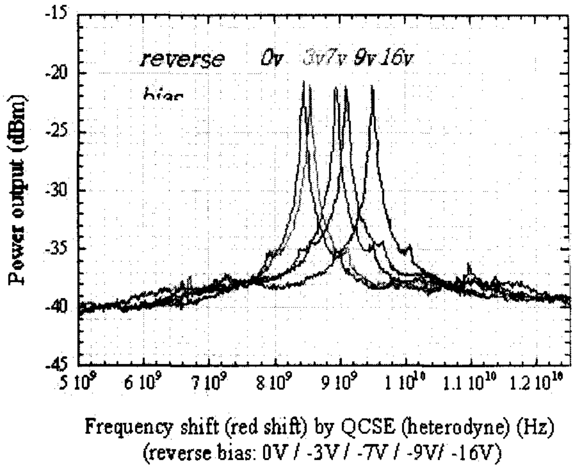

그림 5. QCSE 튜닝에 의한 연속 모드 편이

Fig. 5. Continuous static mode shift due to the QCSE tuning.

Figure 6 shows measured frequency shift due to QCSE (40kV/cm electric field) and calculated

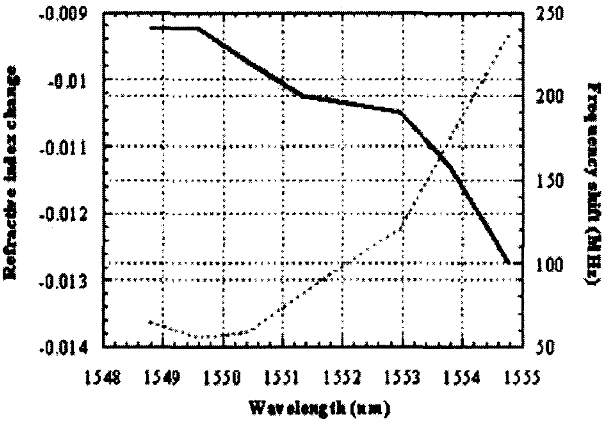

그림 6. 40kV/cm 전기장에서 파장에 대한 측정된 주파수 편이와 굴절계수변화

Fig. 6. Measured static frequency shift and calculated refractive index change versus wavelength at 40 kV/cm electric field.

refractive index change in terms of wavelength spectra. The maximum refractive index change occurs at 1550 nm wavelength, which means the exciton peak wavelength, resulting in the maximum frequency shift of 250 MHz at 40 kV/cm electric field.

V. Multichannel Optical Frequency Channel Synthesis using QCSE Tuning

With an external cavity laser structure in which no efforts are made to weaken internal modes defined by the solitary laser diode cavity, mode selection is relatively easy to observe. Although, according to the analysis, there will be a small amount of continuous tuning accompanied by intensity changes, the mode selecting mechanism is the dominant one. For mode selection the external cavity length l_l was set to an integral multiple of l_o using a micropositioning stage. The laser injection current was maintained constant at 25 mA. The internal mode spacing is about 140 GHz. Figure 7 shows superposed selected laser spectra taken as the tuning element reverse bias was varied from 0 to 10 V. The output power variation was very small, < 1 dB and the selection range was 700 GHz (5.6 nm in wavelength) with side-mode suppression better than 25 dB. To evaluate the refractive index change in the MQW device, the external cavity length and laser injection current were adjusted.

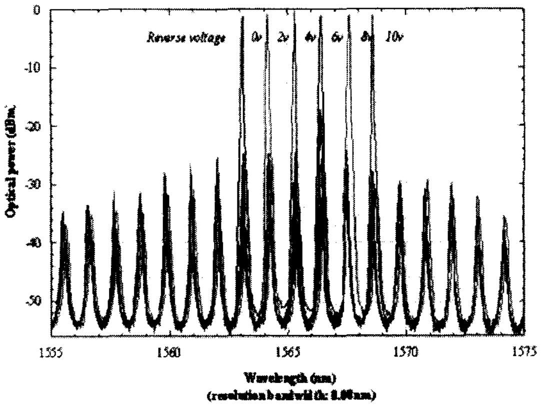

그림 7. 모드선택의 실험 결과

Fig. 7. Mode selection results.

By temperature tuning the gain laser over a 274 ° K to 303 ° K range modes over a wavelength range of 32 nm could be selected. Figure 8 shows a multi channel result by QCSE tuning and 4 step thermal tuning of gain laser which has 30 channels over a 32 nm bandwidth.

At each temperature channels were selected using QCSE tuning giving fast selection speed. Next, the temperature of the gain laser is changed in a step of 8 ° K and several further channels are selected using QCSE. The side mode suppression is better than 25 dB and the gain flatness of the overall channel is less than 1 dB without changing current injection of gain laser. Because the absorption spectrum and the DBR mirror reflection spectrum of the MQW QCSE modulator move to red side and blue side of wavelength, the overall gain of the MQW QCSE multichannel source can be obtained flat over large wavelength region as shown in Figure 8. The stability of the DWDM source depends on the gain laser due to the weak feedback element.

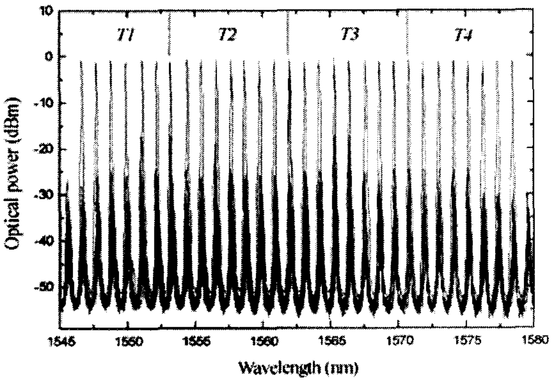

그림 8. 다중채널원의 실험 결과

Fig. 8. Multichannel source results.

Figure 9 shows absorption coefficient and refractive index change for example of QCSE modulator operation. The refractive index change is 78 % of the peak value when 9 V is applied. The absorption changes by only 35/cm over the wavelength region as shown in Figure 9(a). In Figure 9(b), the refractive index change is 1% and the absorption change is 2800/cm at 1578 nm wavelength

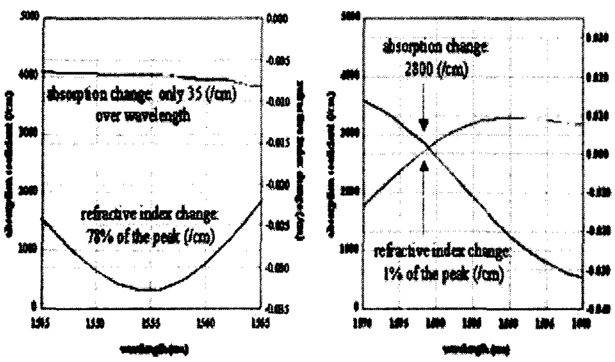

그림 9. -9V 바이어스 전압에서 흡수계수와 굴절계수변화 (a) 1545nm~1565nm 파장대역 (b) 1570nm~1600nm 파장대역에서 흡수계수와 굴절계수의 변화

Fig. 9. Absorption coefficient and refractive index change at -9V bias voltage. (a) absorption change and refractive index change spectrum from 1545 nm to 1565 nm wavelength range (b) wavelength range from 1570 nm to 1600 nm.

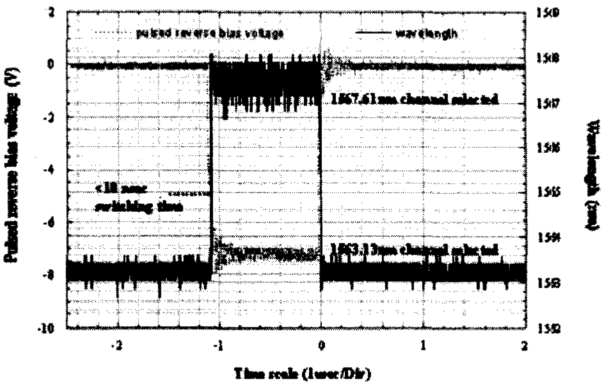

그림 10. 제1모드와 제4모드 간의 채널선택 속도

Fig. 10. Channel selection speed (between 1st channel and 4th channel).

VI. Channel Selection Speed using QCSE

In this QCSE multichannel source, the feedback from the external cavity is so weak and it is just able to turn over the balance between two competing modes and realize mode selection but not strong enough to carry out any continuous tuning. It is clear that the laser system only operates in a single mode, and the optical length change needed for mode selection takes a very short time, therefore the multiple mode operation period is negligible. For instance, the external cavity is modulated by a step signal and takes negligible time to change from one optical length to another. When the laser system is switched from one mode to another by changing the coupled cavity, because the total stored energy change is very small, the rise time of the new mode will be almost equal to the fall time of the old mode as shown in Figure 10. The transient time results of channel selection speed between two channels by QCSE tuning is measured using an etalon based optical frequency discriminator. The transient time for channel selection is seen to be < 10 ns, limited by the rise time of the pulsed voltage source used. Because the -3 dB cut-off frequency of the PIN QCSE tuning element is 10 GHz, the high speed wavelength switching could be achieved using high speed voltage source.

VII. Conclusion

An 1550 nm InGaAsP/InP MQW QCSE tuned multichannel source which can selected 30 channels spaced by 140 GHz over a 32 nm wavelength range has been demonstrated. The continuous static tuning range was 0.8 GHz. The channel selection transient time was less than 10 ns. The channel spacing can be changed to suit the 100 GHz ITU or other WDM grids by using an appropriate length gain laser[12]. By reducing the reflectivity of the interface facet of the gain laser, and applying high reflectivity coating to the other facet of the laser, external cavity length high resolution channel selection can be achieved using QCSE electric field tuning.

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