Control the Transverse mode of Vertical Cavity Surface Emitting Lasers by Anti-Reflection Coating

S. W. Chiou, C. P. Lee
Department of Electronics Engineering
National Chiao Tung University

H. P. Yang, C. P. Sung
Opto-Electronics and Systems Laboratories
Industrial Technology Research Institute
Hsinchu, Taiwan

Abstract

We have successfully developed a selective surface coating technique to control the modal behavior of the ion-implanted vertical cavity surface emitting laser. Using selective deposition of germanium coating by lift-off process, we could spatially control the threshold gain condition of the VCSEL to support the single transverse mode. The threshold current is 7 mA and single transverse mode operation is maintained up to 1 mW. The method is simple and nondestructive compared to other techniques.

Keywords: Key words: VCSEL, single-mode, proton implant, and AR coating

Introduction

Vertical cavity surface emitting laser (VCSEL) has emerged as an attractive light source for next generation fiber communication system because of its inherent two-dimensional configuration and circular output beam shape [1-3]. However, the relative wide output aperture of a typical VCSEL leads to higher-order transverse modes which degrade its ability for high speed and long distance data communication. Therefore, it is important to achieve stable and single transverse mode operation of VCSEL.

Several attempts have been made to obtain the stable single transverse mode. The most popular way is to use an oxide-confined aperture to make the device small enough to support only the fundamental mode [4]. This approach has the disadvantage of increased series resistance and reduced output power because of the reduced current aperture. Recently, another technique, which utilizes the surface relief etching, was developed and was effective to suppress the higher order modes [5]. This technique, which relies on the precise control on the etched thickness of the top AlAs layers in the DBR, allows only fundamental mode oscillation by keeping the higher order modes off-resonance. But since the etching was done on part of the top DBR, it may cause the reliability problem. In this paper, we describe a new technique, to obtain the single transverse mode operation. The mode was selected by selectively controlling the thickness of an additional germanium coating on the surface. We could spatially control the threshold gain of the VCSEL to support only the single fundamental mode.

Design and Fabrication

The principle behind the mode selection lies on the spatially dependent cavity loss introduced by selective deposition or removal of an additional coating on the surface. Since the length of a VCSEL cavity is two order of magnitude shorter than an edge-emitting laser, the mirror reflectivity of the DBRs required to achieve threshold gain is very high (~99.99%). Additional material coating over the DBR would render the mirror reflectivity to a lower value so that the lasing operation can no longer be sustained.

Fig. 1 shows the dependence of the peak reflectivity of a DBR with 20 pairs of AlAs/AlGaAs on the refractive index of a surface AR-coating layer. Taking TiO2 (n=2.45) for example, the peak reflectivity of the DBR drops from 99.83% to 99%. In this study, we choose germanium as the AR-coating material, which has a refractive index of 5.2+0.65j

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at 850nm. With such a high refraction index of 5.2, the peak reflectivity of the DBR can be reduced down to 96%. Thus, we could easily change the threshold gain condition of the VCSEL by additional mirror coating. By selective deposition of this additional coating, the mirror loss, or the threshold gain required, can be spatially varied. In other words, by selective control of the opening size of AR coating, we can spatially change the threshold condition of VCSEL and therefore maintain the stable fundamental transverse mode at all range of driving current.

The devices investigated are 850 nm VCSELs with a proton implanted-isolated area with a diameter of 20 μm. After proton implantation, a Ti/Pt/Au ring contact with 15-μm inner diameter was deposited for p-side contact. And the AuGe/Ni/Au n-type contact was evaporated on the backside. Then a 1/4 λ thick germanium film was deposited on the top surface with a 5 μm diameter opening at the center defined by photolithography and lift-off. The device was then bonded for test. Fig. 2 shows the SEM photograph of our fabricated VCSEL. The cross section of the device is also shown schematically in the figure.

Results

To demonstrate the operation principle of our single-mode VCSEL, we have compared several devices with different kinds of surface coating. First, VCSELs with different coatings and without coating were fabricated and measured as reference. Then, our newly designed VCSELs with 5 μm opening of Ge coating were investigated.

Fig. 3 shows the light versus current (L-I) characteristics of VCSEL with a TiO2 coating, a Ge coating and without coating. The typical threshold current of 15-μm-implanted VCSEL without surface coating is 5 mA and the external quantum efficiency is 0.25 W/A. For the VCSEL with TiO2 coating, the threshold current increases to 14 mA and the quantum efficiency increases to 0.5 W/A. The increased threshold current and quantum efficiency is due to the reduced reflectivity of the top DBR. For the VCSEL with a Ge coating, the threshold current further increases to 21 mA while the quantum efficiency remains the same as the VCSEL without surface coating. The rather lower quantum efficiency is due to the absorption of the Ge coating.

Fig. 4 shows the L-I curve of the VCSEL with a 5 μm opening in the Ge coating. The threshold current is 7 mA. This slightly increase in threshold current is due to the current crowding effect in the relatively large proton defined aperture [6]. The small lasing window at the center of the aperture is located at where the injection current is less efficient, causing slight increasing in threshold current. Fig. 5(a) shows the lasing spectra of the laser at different driving currents. We can see that the single mode operation is obtained as long as the current is below 12 mA, which is 1.7 times of the threshold current. Between 12 mA and 17 mA, the laser has two modes. Above 17 mA, the single mode operation returns and it remains till the laser stop operation due to heating effect. The mode change can be also seen in the L-I curve shown in Fig. 4. The two kinks marked on the curve indicate the onset and the end of the two modes operation. The higher order mode is due to the non-uniform carrier depletion at the lasing condition (spatial hole burning). Fig. 5(b) shows the spectra of an original VCSEL without Ge coating. Multi-mode operation is observed at all levels of the driving current. From Fig.4 and Fig.5, we can see that using selective Ge coating, we can achieve fundamental transverse mode operation in our VCSELs up to 1.7 times of the threshold current with a maximum output power of 1 mW.

Fig. 6 shows the magnified spectrum of a VCSEL driven at 11 mA. The mode suppression ratio is over 30 dB. The rather lower symmetric side peaks are not from higher order modes but due to the resonance-cavity-enhanced spontaneous emission from the area that is covered by Ge coating [7].

Conclusion

We have successfully developed a process to control the modal behavior of the implanted VCSELs using a selective AR coating on the top surface. Through Ge AR-coating with a 5 μm window opening, we can obtain fundamental transverse mode operation from devices with a 20 μm implant defined aperture and a 15 μm contact ring. The devices can maintain fundamental transverse mode up to 1.7 times the threshold current with the output power of 1 mW. The mode suppression is over 30 dB. Comparing to the conventional surface relief technique [5], our process is simple and does not cause destructive damage to the DBR mirror. This technique should be useful for the realization of low resistance single mode VCSELs with high output power and extended lifetime.

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Figure caption:

Figure 1. The peak reflectivity versus the refractive index of a surface AR-coating of a 20 pairs of AlAs/AlGaAs DBR for 850 nm VCSEL.

Figure 2. The SEM photograph of the top laser facet with a Ge AR-coating and a 5 μm window.

Figure 3. The light versus current (L-I) characteristics for the VCSELs with TiO_2, Ge AR-coating films, and without AR-coating.

Figure 4. The L-I curve of a VCSEL with a Ge AR-coating and a 5 μm window.

Figure 5(a). The spectra of the VCSELs with a Ge AR-coating and a 5 μm window measured at 7 mA, 9mA, 11mA, 15 mA, 20 mA

5(b). The spectra of a VCSEL without surface AR-coating measured at 5 mA, 7 mA, 9 mA, 15 mA, 20 mA.

Figure 6. The magnified spectrum of a VCSEL with a Ge AR-coating and a 5 μm window measured at the 11 mA.

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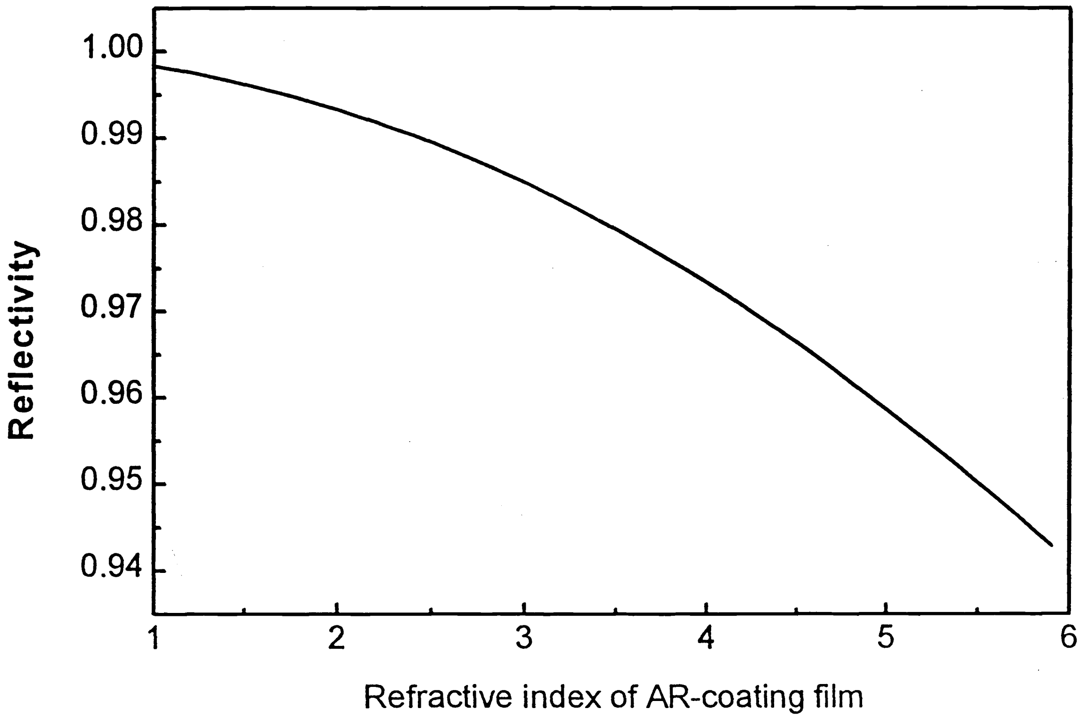

Reflectivity
1.00
0.99
0.98
0.97
0.96
0.95
0.94
1
2
3
4
5
6
Refractive index of AR-coating film

Fig. 1.

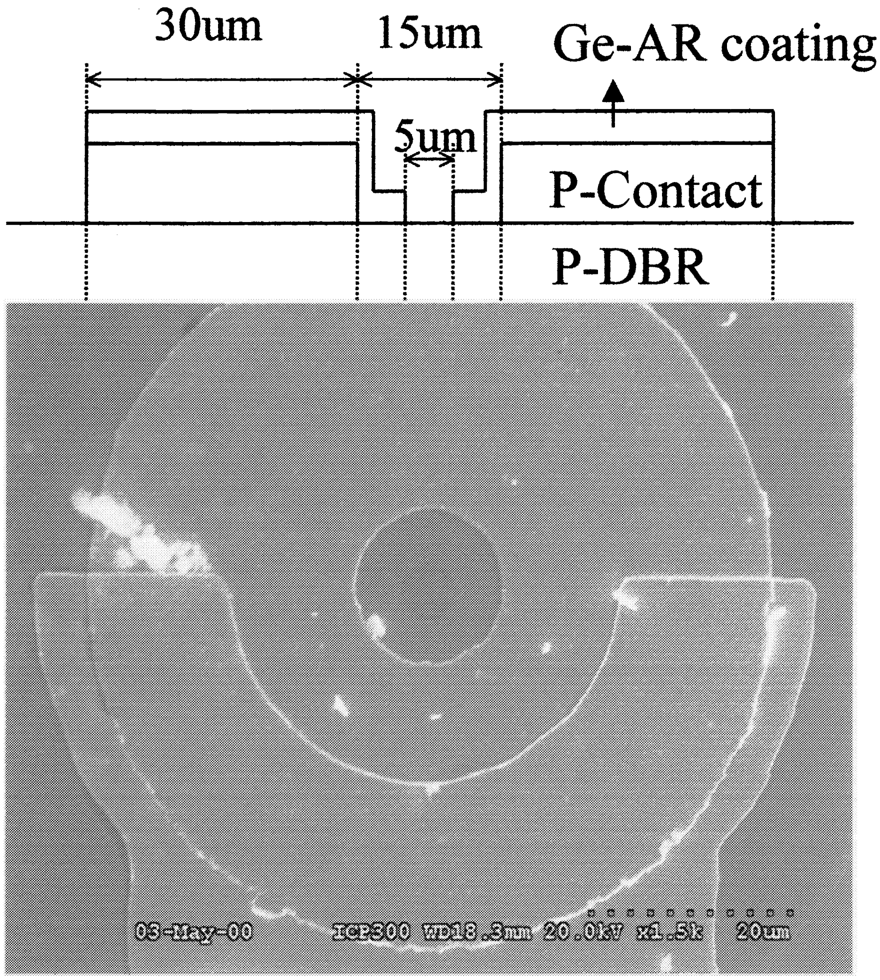
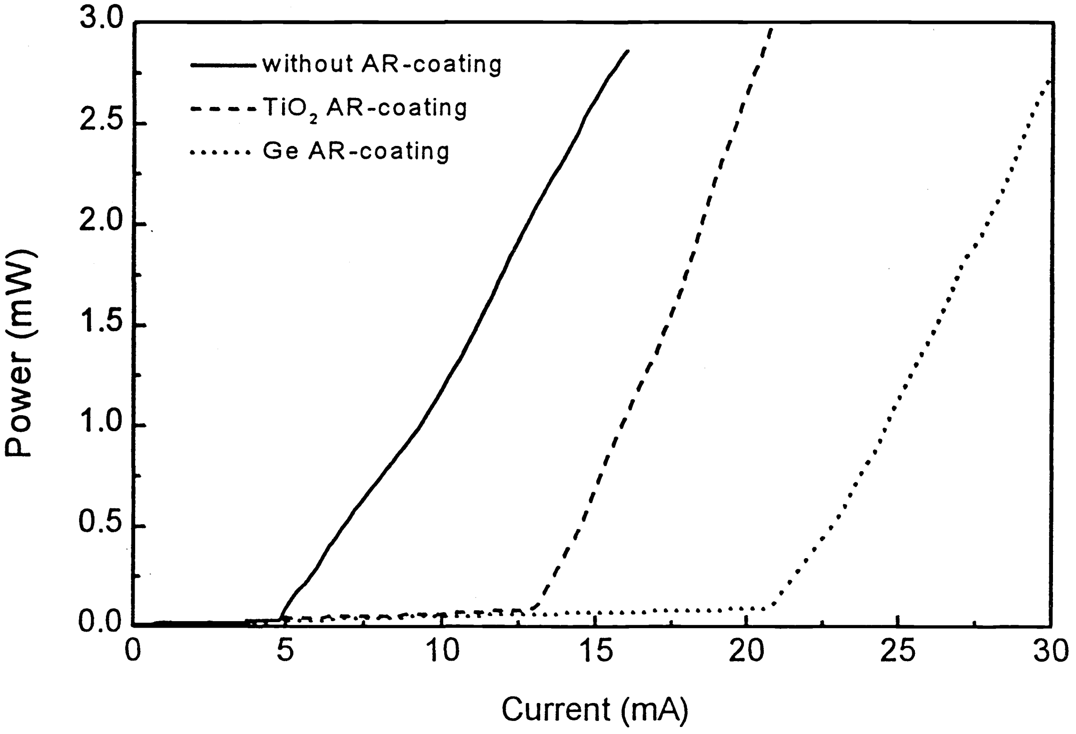
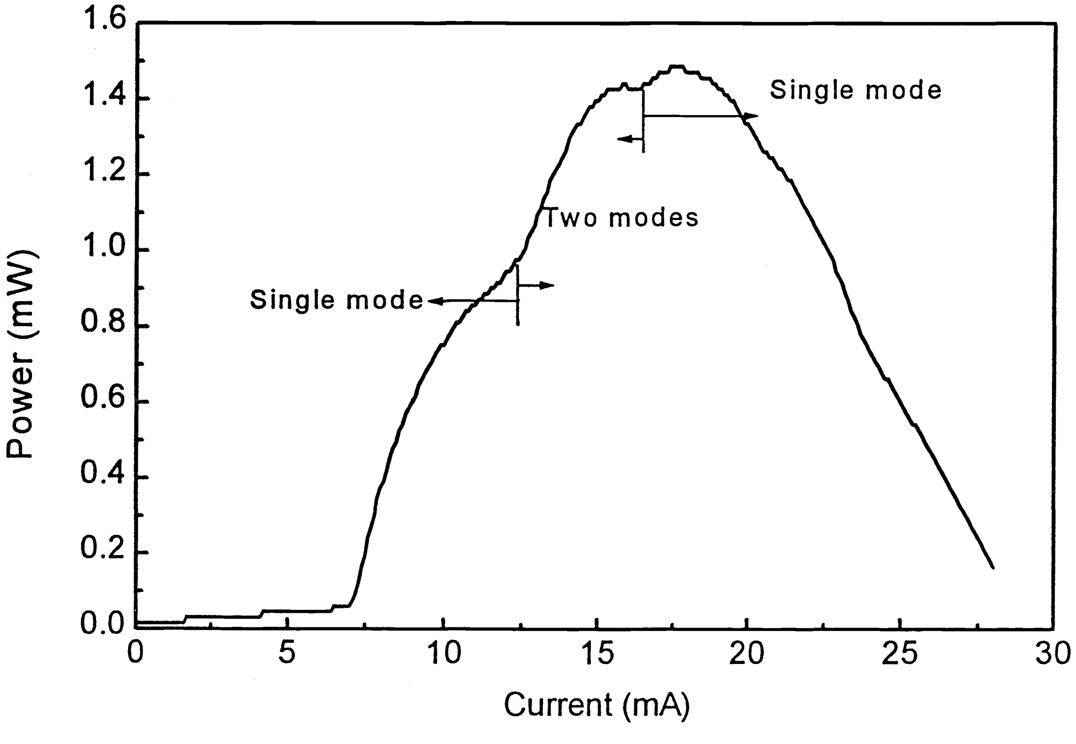


Fig. 2.
S. W. Chiou



without AR-coating
TiO$_2$ AR-coating
Ge AR-coating
Power (mW)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Current (mA)
0
5
10
15
20
25
30

Fig. 3.



Single mode
Two modes
Single mode
Power (mW)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Current (mA)
0
5
10
15
20
25
30

Fig. 4.

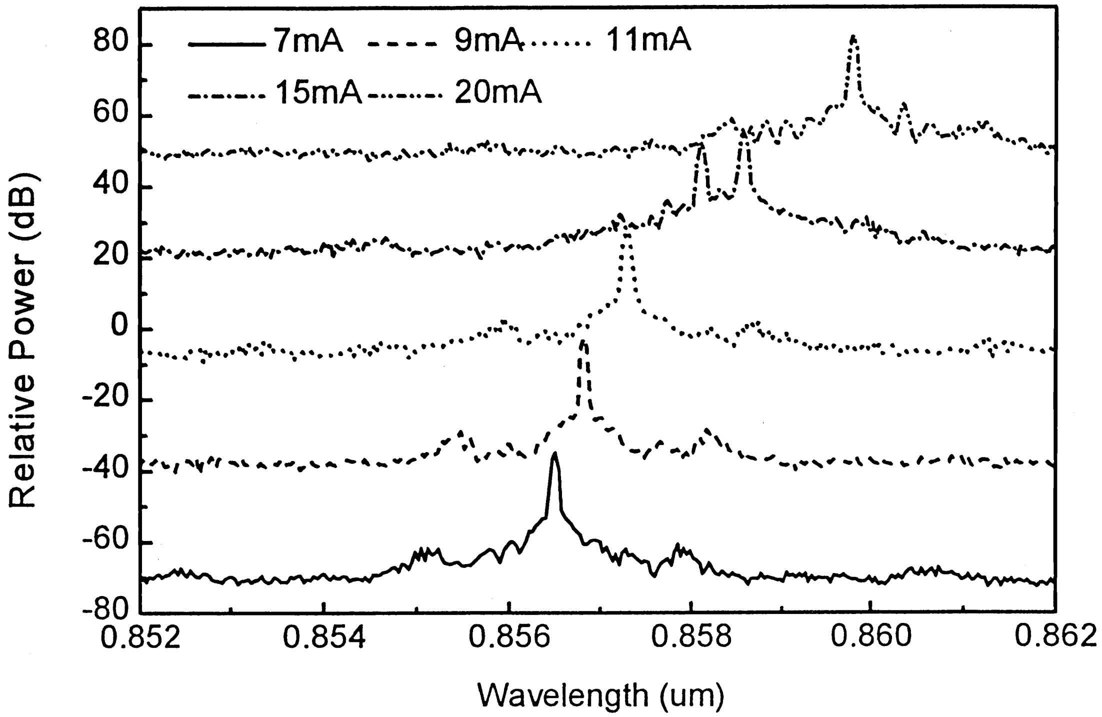

7mA
9mA
11mA
15mA
20mA
80
60
40
20
0
-20
-40
-60
-80
0.852
0.854
0.856
0.858
0.860
0.862
Relative Power (dB)
Wavelength (um)

Fig. 5(a).

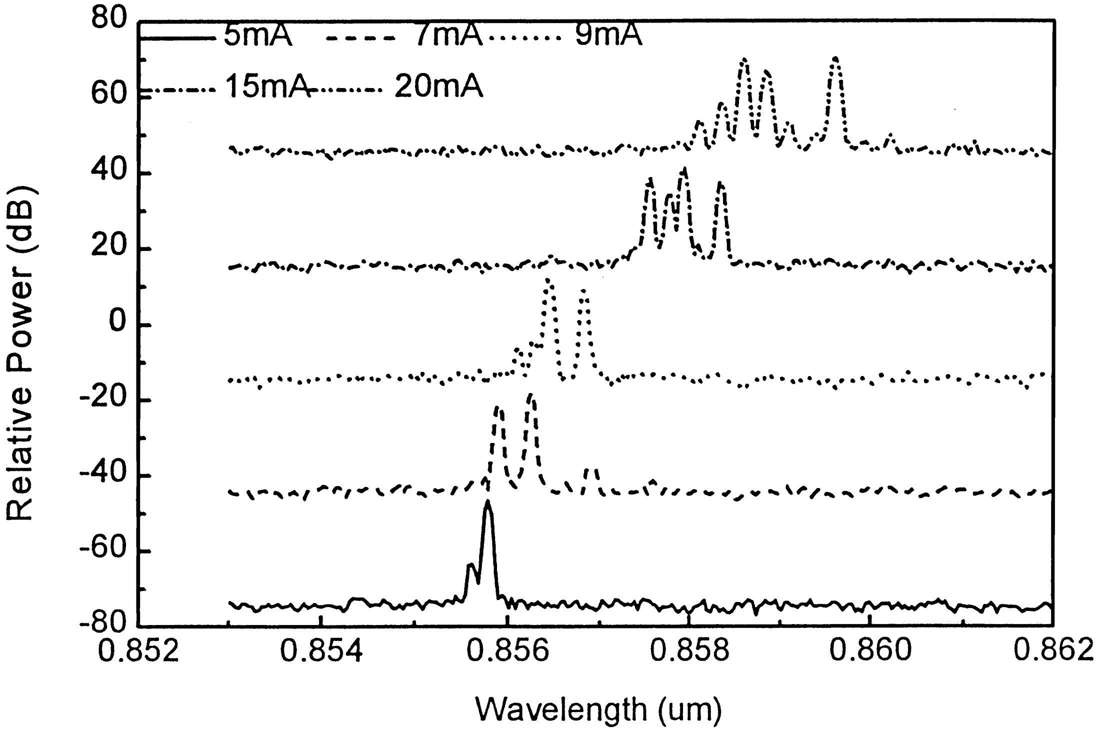

5mA
7mA
9mA
15mA
20mA
80
60
40
20
0
-20
-40
-60
-80
0.852
0.854
0.856
0.858
0.860
0.862
Relative Power (dB)
Wavelength (um)

Fig. 5(b).

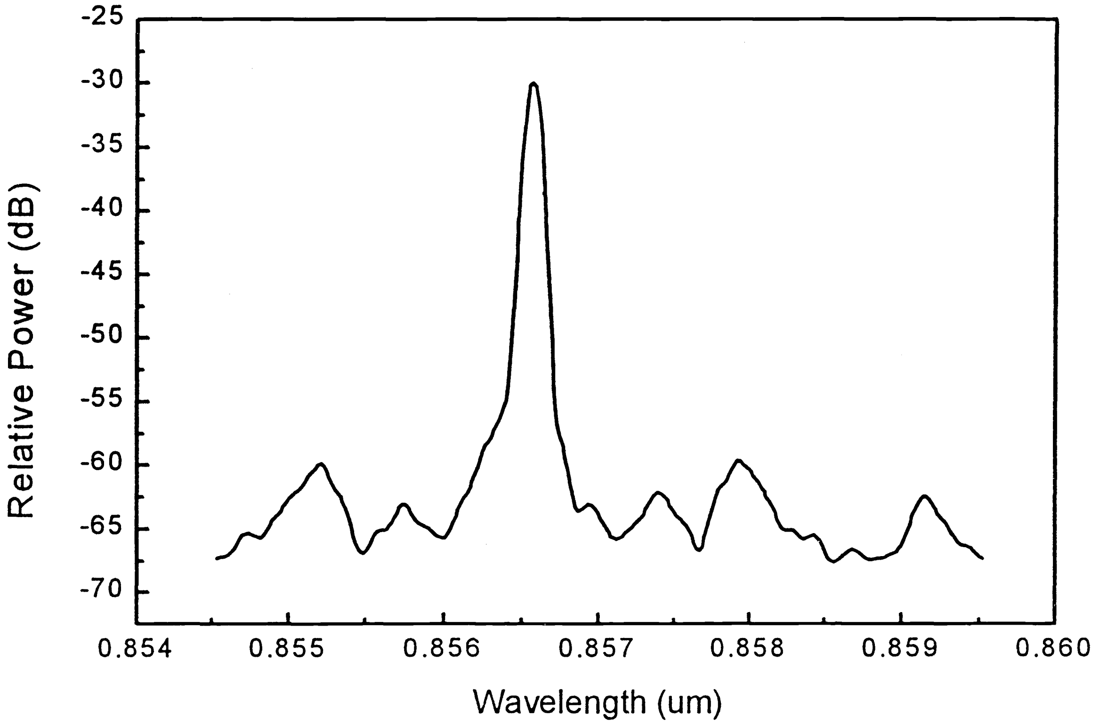

-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
Relative Power (dB)
0.854
0.855
0.856
0.857
0.858
0.859
0.860
Wavelength (um)

Fig. 6.