Temperature dependence of the reflectivity in absorbing Bragg reflectors

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Abstract: The reflectivity of absorbing Bragg reflectors consisting of a GaAs/AlAs Bragg mirror and a InGaAs/InGaAsP multiple-quantum-well cavity layer was studied as a function of temperature. An absorption dip in the stop band due to the optical confinement of the Fabry-Perot resonance was observed in the reflectivity spectra. The absorption intensity of the dip increased with temperature and was explained by the resonant coincidence of the Fabry-Perot cavity mode and the quantum-well absorption. The temperature-dependent reflectivity spectra were successfully reproduced using the transfer matrix method and the linear dependence of the refractive index on temperature.

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References and links
1. Introduction

Bragg reflectors have attracted a great deal of attention owing to their applications in optoelectronic devices, such as microcavity light-emitting diodes and vertical-cavity surface emitting lasers (VCSELs). These devices usually require highly transparent dielectric layers to eliminate any loss due to the optical absorption in the Bragg reflectors. However, saturable Bragg reflectors, consisting of semiconductor quantum wells embedded in Bragg reflectors, are designed to increase optical absorption by photon localization over a spectral range of the stop band. The enhancement of optical absorption plays an important role in increasing the efficiency of absorption saturation in semiconductor and solid-state mode-locked lasers [1-2]. Furthermore, absorbing media are sometimes employed along with layer-by-layer distribution of the refractive index to control the optical absorption in Bragg reflectors [3]. The optical absorption can then be enhanced or reduced according to the distribution both of the refractive index and of the absorbing media in the Bragg reflectors. Since the absorption effect is essential in such optoelectronic devices an understanding of the fundamental properties of the optical absorption in the Bragg reflectors is desired. This topic has been much investigated [4-6]. The optical absorption of absorbing Bragg reflectors due to the cap-layer effect has been studied and a spectral dip in the high reflection band has been shown to originate from the absorption layers [4]. The light absorption of the Bragg reflectors has been determined in the framework of the transfer matrix method and the enhancement of exciton resonance has been theoretically demonstrated when the Bragg interference condition is met at the exciton resonance frequency [5]. Additionally, the carrier dynamics in the absorption saturation in a nonlinear Bragg reflector were studied and carrier-carrier scattering was proven to increase due to high-density photon localization [6]. To our knowledge, no work has yet investigated the thermal effect of optical absorption on the absorbing Bragg reflectors. The thermal features of the optical absorption of Bragg reflectors are expected to be important for devices containing Bragg-reflector structures, such as the saturable Bragg reflectors and VCSELs. For example, since the absorption intensity is essential for generating pulses in the passive and hybrid mode locking, the thermal features of optical absorption of the absorbing Bragg reflectors are important when the absorbing Bragg reflectors are used as saturable absorbers.

This paper studies the reflectivity spectra of absorbing Bragg reflectors as a function of temperature. A dip in the high reflection band of the Bragg reflectors in reflectivity is attributed to optical absorption from the Fabry-Perot cavity mode between the air/cavity-layer interface and the Bragg mirror. As the temperature is decreased, the dip position shifts toward the shorter wavelength and the absorption intensity of the dip decreases. The temperature-dependent reflectivity spectra of the absorbing Bragg reflector were analyzed using the transfer matrix method and the linear dependence of the refractive index on temperature.

2. Experiment

The absorbing Bragg reflectors studied here consisted of a GaAs/AlAs distributed Bragg reflector (DBR) and an absorbing layer. The DBR, consisting of 27 pairs of GaAs/AlAs quarter-wave stacks, was used to enhance the reflectivity and bandwidth of the reflector. The
absorbing layer had two sets of 15 InGaAs/InGaAsP strain-compensated multiple quantum wells separated by 80 nm of lattice matched InGaAsP. The compressive strain wells and tensile strained barriers resulted in a strain-compensated quantum well, which was demonstrated to yield a low effective loss due to the lifting of the critical thickness constraint. A novel wafer-bonding technique was employed to integrate the InP-based quantum wells (absorbing layer) with the GaAs-based Bragg mirror since the GaAs/AlAs DBR is grown on GaAs substrate [7]. In this structure, a cavity layer was formed by the interfaces of the DBR/absorbing-layer and the air/absorbing-layer. The sample was mounted in a close-cycle helium cryostat, at temperatures between T=11 and T=300 K. The absorption characteristics of the samples were characterized using reflectivity spectra. Light from a halogen lamp was normally incident on the sample and the reflected light was dispersed by a monochromator and detected by a Ge detector.

3. Results and discussion

Figure 1 (a) shows the measured reflectivity spectrum of the sample at normal incidence at room temperature. The spectrum is a typical reflectivity of the Bragg reflectors, but including an extra large dip at 1545 nm in the high-reflectance band (stop band). From the reflectivity measurement, we obtained the center wavelength of the stop band (λ), which is determined by the optical thickness, d, of the Bragg reflectors (d = n_d/4n = λ/4), where n is the refractive index, and; n_air and λ are the wavelength of light in free space and the layered material, respectively). Fig. 1 (b)-(e) show the measured reflectivity spectra as the temperature is decreased from 300 to 11 K. The falling

![Fig. 1. Measured reflection spectra of absorbing Bragg reflectors as a function of temperature.](image-url)
variation of the absorption coefficient for a direct band-gap semiconductor is less pronounced [9]. This problem is discussed in detail below.

To investigate the thermal behavior of the dip in the reflectivity spectra, the reflectivity was calculated using the matrix formulation for multi-layer structures [10]:

\[
\begin{pmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{pmatrix}
= D_0^T \cdot D_c \cdot P_c \cdot D_c^T \cdot \left[ D_L \cdot P_L \cdot D_L^T \cdot D_H \cdot P_H \cdot D_H^T \right]^{27} \cdot D_H^T,
\]

(1)

where \(D_0, D_c, D_L, \) and \(D_H\) are the dynamic matrices for free space, the cover layer, GaAs, and AlAs, respectively; \(P_c, P_L, \) and \(P_H\) are the propagation matrices for the cavity layer, GaAs, and AlAs, respectively. To include the optical absorption (a loss term), the refractive index of the cavity layer is assumed to have an imaginary part, used as an adjustable parameter to fit the experimental data. The reflectivity shows a dip in the stop band when the loss in the cavity layer is included. In the calculations, material parameters were determined from the literature and our experimental data. Figure 1 (a) and references [11-12] are used to estimate the refractive indices of the GaAs and AlAs since the bandwidth of the stop band \(\Delta\omega(T)\) depends only on the refractive indices of these two materials [13]:

\[
\Delta\omega(T) = \frac{4}{\pi} \cdot \sin^{-1} \frac{n_H(T) - n_L(T)}{n_H(T) + n_L(T)} \cdot \omega(T),
\]

(2)

where \(\omega(T)\) is the central angular frequency of the stop band, and \(n_H\) and \(n_L\) are the refractive indices of the GaAs and AlAs, respectively. If the refractive indices were taken directly from the references, the bandwidth of the stop band would be 183 nm, which is about 34 nm wider than the experimental result. However, using the adjusted values results in agreement with the experimental bandwidth. At 1550 nm the corresponding values are 3.37 for GaAs and 3.02 for AlAs, which are within 3% of the values in the literature. For the thermal dependence of the refractive indices of GaAs and AlAs near 1550 nm between 11 and 300 K, there is no data have been reported. Since the thermal dependence of the refractive indices of these two materials is strongly linear with temperature [14], refractive indices were first fitted from the angle-dependent photoluminescence at 11 and 300 K, and then deducing the temperature-dependent refractive indices by linear interpolation. The resulting values were \(6 \times 10^{-3}/^\circ C\) and \(2.1 \times 10^{-4}/^\circ C\) for GaAs and AlAs, respectively. With these optical constants, Eq. (1) was used to simulate the reflectivity between 11 and 300 K. Figure 2 shows the calculated reflectivity spectra as a function of temperature. Comparing Fig. 2 to Fig. 1, the simulated curves well reproduce the important features of the stop band, the side lobes, and the dip, showing good agreement between experimental data and calculations. It is notable that all the
reflectivity intensities of the stop band and side lobes in Fig. 2 were not adjusted in the calculations. The change of their magnitudes is the result of the thermal dependence of the refractive indices of the cavity layer and DBR. In Fig. 2, the imaginary part of the refractive index of the cavity layer was determined from the fit of the dip in the stop band. Accordingly, the absorption coefficient $\alpha$ can also be found according to: $\alpha = \frac{\pi \kappa}{\lambda_{\text{air}}}$. Taking into account $\kappa$ and $\lambda_{\text{air}}$, the absorption coefficient of the cavity layer at the dip position is obtained. Table 1 lists the dip positions in the stop band, $\kappa$, and $\alpha$, as functions of temperature. Table 1 shows that the room-temperature absorption coefficient of the cavity layer at 1545 nm is 3985 cm$^{-1}$, which is close to the value in the literature [15]. However, the absorption coefficient of the cavity layer decreases as the temperature is decreased. This thermal effect is inconsistent with the theoretical model, which shows that the temperature variation of the absorption coefficient is negligible for a direct band-gap semiconductor [9]. The decreasing absorption coefficient with decreasing temperature can be explained by the fact that the absorption of the cavity medium (multiple quantum wells) is detected by the filtering of the Fabry-Perot cavity mode. Therefore, the coincidence of the absorption energy of the multiple quantum wells with the energy of the Fabry-Perot cavity mode is crucial. The spectral position of the quantum-well absorption can be obtained by the in-plane photoluminescence, where the luminescence is detected parallel to the sample surface [16]. At

Table 1. Values of dip positions, $\kappa$, and $\alpha$, as functions of temperature.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>11</th>
<th>110</th>
<th>170</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip position (nm)</td>
<td>1523</td>
<td>1528</td>
<td>1532</td>
<td>1539</td>
<td>1544</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.0029</td>
<td>0.0076</td>
<td>0.014</td>
<td>0.03</td>
<td>0.049</td>
</tr>
<tr>
<td>$\alpha$ (cm$^{-1}$)</td>
<td>237</td>
<td>625</td>
<td>1148</td>
<td>2450</td>
<td>3985</td>
</tr>
</tbody>
</table>

300 K, the spectral position of the quantum-well absorption (~1550 nm) coincides with that of the cavity mode (1548 nm), such that the absorption intensity is strong. The shift of the quantum-well absorption with decreasing temperature (~0.23 nm/°C) far exceeds that of the cavity mode (~0.08 nm/°C). As a result, the spectral position of the quantum-well absorption does not coincide with that of the cavity mode, leading to reduced absorption at low temperature.

The temperature dependence of the bandwidth of the stop band extracted from Fig. 1 is displayed, as solid circles, in Fig. 3. As the temperature is increased, the bandwidth exhibits a thermal broadening due to the increase of the contrast of the refractive indices ($n_U - n_L$). The solid line in Fig. 3 shows the calculations by using Eq. (2). In the calculations the temperature dependence of the refractive indices of both GaAs and AlAs is assumed to be linear. As can be seen, the temperature dependence of the bandwidth of the stop band with calculations agrees reasonably with the experimental values. The measured temperature dependence of the center wavelength of the stop band and that of the dip position are shown, as solid circles, in Figs. 4 and 5, respectively. Again, these experimental results correlate well with theoretical calculations. The consistency between the experiments and the calculations...
in our studies indicates that the assumed linear dependence of the refractive index on temperature is a good approximation over a wide range of temperatures.

![Fig. 3](image1.png)

**Fig. 3.** Temperature dependence of the experimentally measured (solid circles) and theoretically predicted (solid line) bandwidth of the stop band.

![Fig. 4](image2.png)

**Fig. 4.** Temperature dependence of the experimentally measured (solid circles) and theoretically predicted (solid line) center of the stop band.

![Fig. 5](image3.png)

**Fig. 5.** Temperature dependence of the experimentally measured (solid circles) and theoretically predicted (solid line) dip position in the stop band.

### 4. Conclusion

In conclusion, absorbing Bragg reflectors, which consist of the GaAs/AlAs Bragg mirror and the InGaAs/InGaAsP multiple-quantum-well cavity layer, were studied by temperature-dependent reflectivity. An absorption dip in the stop band originating from the optical confinement of the Fabry-Perot cavity was observed in the reflectivity spectra. The measured reflectivity of the absorbing Bragg reflector was modeled by the transfer matrix method with a complex refractive index. The calculated reflectivity spectra well reproduced the experimental spectra, assuming that the refractive index depended linearly on temperature. In addition, the increased absorption intensity of the dip with increasing temperature can be understood by the resonant coincidence of the Fabry-Perot cavity mode and the quantum-well absorption.

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