Multi-cavity Resonance Enhanced Wavelength Demultiplexing Photodetectors

Xiaomin Ren, Kai Liu, Yongqing Huang, Hui Huang, Liyi Liu
(Beijing University of Posts and Telecommunications,, Beijing 100876, China)
Xiaoyu Ma, Qiwei Liao, Xuejun Kang,
(Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)
Joe C. Campbell
(Microelectronics Research Center, University of Texas, Austin, TX 78712, USA)

Abstract: Based on the concept of resonant-cavity-enhanced (RCE) photodetector with a single-cavity configuration, we proposed and developed multi-cavity resonance-enhanced wavelength-demultiplexing photodetectors with two-subcavity and three-subcavity configurations for high-speed WDM applications. A linewidth as narrow as 1.4nm and a quantum efficiency larger than 50% have been achieved simultaneously.
Keywords: resonant-cavity-enhanced (RCE) photodetector, multi-cavity configurations, wavelength-devision-multiplexing (WDM), resonance-enhanced wavelength-demultiplex-ing (REWDM) photodetectors, semiconductor optoelectronic devices, spectral response linewidth narrowing

1. INTRODUCTION

More and more attention has been paid in recent years to a new variety of photodetectors, i.e. the resonant cavity enhanced (RCE) photodetectors[1]. However, most of them are featuring single resonant cavity configuration and wide response linewidth. To make this kind of devices suitable for WDM system applications, we proposed and developed a series of multi-cavity resonant enhanced wavelength de-multiplexing photodetectors, including two-subcavity[2][3] and three-subcavity conf-igurations. The latter featuring three cavities, i.e. the filtering cavity, the spacer cavity and the absorption cavity. By adopting this structure, high quantum efficien-cy, high speed and narrow spectral linewidth can be obtained simultane-ously. Bas-ed on intensive theoretical investigations, such a three-cavity photodet-ector has been actually fabricated and characterized. A linewidth as narrow as 1.4nm (FW-HM) and a quantum efficiency larger than 50% have been achieved. Theoret-ically predicted linewidth and quantum efficiency are still better and could be less than 1nm and up to 90%, respectively. Such devices are very promising for wavelength division multiplexing (WDM) applications. The theory and experiments will be described in the following sections.

2. THEORY

A. Device Structure

The proposed device structure is illustrated in Fig. 1. It features four mirrors that may be made of quarter-wave stacks of semiconductor compounds or dielectric materials. The top mirror (mirror 1) and the upper middle mirror (mirror M1) form the filtering cavity. The absorption layer is sandwiched between the lower middle mirror

(mirror M2) and the bottom mirror (mirror 2), and they together form the absorption cavity. Between the two middle mirrors M1 and M2 is the spacer cavity, which plays an important role for the performance optimization.

B. Analysis Model

An analysis model is given in Fig. 2. The reflectivities of mirror 1, mirror M1, mirror M2, and mirror 2 are R1, RM1, RM2 and R2 respectively. For the convenie-nce of comparison with normal RCE photodetectors, in Fig. 2, the multi-layer stru-cture from mirror 1 to mirror M2 can be equivalently represented by mirror 1’ and the corresponding reflectivity by R1’.

According to Fig. 2 and the reference[4], the relationship between (EiR, EiL) and (EoR, EoL), (EbR, EbL) can be determined with the following formulas:

$$\begin{pmatrix} E_{iR} \\ E_{iL} \end{pmatrix} = S_{FC} \cdot U_{SC} \cdot S_{AC} \cdot \begin{pmatrix} E_{oR} \\ E_{oL} \end{pmatrix}$$

$$U_n = \begin{pmatrix} \exp(\alpha_n \times l_n / 2 + j\varphi_n), 0 & \\ 0, & \exp(-\alpha_n \times l_n / 2 - j\varphi_n) \end{pmatrix}$$

$$W_{nn+1} = \frac{1}{2} \times \begin{pmatrix} 1 + \frac{n_{n+1}}{n_n}, 1 - \frac{n_{n+1}}{n_n} \\ 1 - \frac{n_{n+1}}{n_n}, 1 + \frac{n_{n+1}}{n_n} \end{pmatrix}$$

$$\begin{pmatrix} E_{iR} \\ E_{iL} \end{pmatrix} = S_{FC} \cdot U_{SC} \cdot S_{MirrorM2} \cdot S_{ab} \cdot \begin{pmatrix} E_{bR} \\ E_{bL} \end{pmatrix} \quad (1)$$

where $S_{FC} = S_{Mirror1} \cdot U_f \cdot S_{MirrorM1}$,

$S_{AC} = S_{MirrorM2} \cdot S_{Cavity} \cdot S_{Mirror2}$

$S_{cavity} = U_a \cdot W_{ab} \cdot U_b \cdot W_{bc} \cdot U_c$, $S_{ab} = U_a \cdot W_{ab}$,

$S_{Mirror1}$, $S_{Mirror2}$, $S_{MirrorM1}$ and $S_{MirrorM2}$ are the transfer-matrixes of mirror 1, mir-ror 2, mirror M1 and mirror M2 respectively, SFC is the transfer-matrix of filtering cavity, SAC the transfer-matrix of the absorption cavity. Un (n= SC, a, b, c) is the phase-matrix representing the light traveling through the corresponding region. An-d Wn, n+1 (n= a, b; n+1= b, c) is the matrix corresponding to the interface between region n and region n+1.

C. Quantum Efficiency

To calculate the quantum efficiency of the quantum efficiency, the following formula is assumed:

$$\begin{aligned} S &= S_{FC} \cdot U_{SC} \cdot S_{AC} \\ S' &= S_{FC} \cdot U_{SC} \cdot S_{MirrorM2} \cdot S_{ab} \end{aligned} \quad (2)$$

Then the electric field of the lightwave in the absorption layer can be derived from formula (1) and (2) as:

$$E_{bR} = \frac{S'_{22} - S'_{12} \times S_{21} / S_{11}}{|S'|} \times E_{iR}$$

$$E'_{bL} = \frac{S'_{11} \times {S_{21}}/{S_{11}} - S'_{21}}{\left| S' \right|} \times \exp(\alpha_b \times l_b / 2 + j\varphi_b) \times E_{iR} \qquad (3)$$

The power absorbed in the absorption layer can thus be written as

$$P_{absorption} = (P_{bR} + P'_{bL}) \times (1 - \exp(-\alpha_b \times l_b)) \qquad (4)$$

where

$$P_{bR} = \frac{n}{2\eta_0} \times \left| E_{bR} \right|^2, \qquad P'_{bL} = \frac{n}{2\eta_0} \times \left| E'_{bL} \right|^2 \qquad (5)$$

Finally, the quantum efficiency of the photodetector is calculated from formu-la (4) and (5) as:

$$\eta = \frac{1}{\left| S' \right|^2} \times \left[\left| S'_{22} - S'_{12} \times \frac{S_{21}}{S_{11}} \right|^2 \times (1 - \exp(-\alpha_b \times l_b)) + \left| S'_{11} \times \frac{S_{21}}{S_{11}} - S'_{21} \right|^2 \times (\exp(\alpha_b \times l_b) - 1) \right] \times \frac{n_b}{n_0}$$

D. Mirror Reflectivity

The reflectivities of all the mirrors in this structure can be derived from their transfer-matrixes:

$$R_i = (|S_{i21}/S_{i11}|)^2 \text{, i= 1, 2, M1, and M2} \qquad (6)$$

To calculate the reflectivity of Mirror 1' in Fig. 3, we assume the following transfer-matrix:

$$S_1' = S_{FC} \cdot U_{SC} \cdot S_{MirrorM\ 2} \qquad (7)$$

Then R_1' is obtained as:

$$R_1' = (|(S_1')_{21}/(S_1')_{11}|)^2 \qquad (8)$$

3. DESIGN AND EXPERIMENTAL RESULTS

The device was grown by MOCVD on a GaAs substrate. Its bottom mirror was grown after the deposition of one n-type 0.5μm-thick GaAs buffer layer. The DBR was n-doped and consisted of 20-periods of alternating λ/4 thick n-type Al.1Ga.9-As and AlAs (λ =0.85μm). Following the deposition of the bottom mirror, a PIN photodetector structure was grown. It was composed of one 0.12μm thick n-type AlAs spacer layer, one 0.05μm thick i-type Al.1Ga.9As spacer layer, one 0.135μm thick i-type GaAs absorption layer, one 0.05μm thick i-type Al.1Ga.9As spacer la-yer and one 0.12μm p-type AlAs spacer layer. And then, the top mirror of the abso-rption cavity was grown. It was constructed by 6 pairs of alternating λ/4 thick p-type Al.1Ga.9As and AlAs layer. Afterward, a p-type AlAs layer with a thickness of 71nm was grown as the spacer cavity. The filtering cavity was defined by two DBRs. The bottom DBR and the top DBR were formed by 11-periods and 12-perio-ds of alternating λ/4 thick p-type Al.1Ga.9As and AlAs layer, respectively. Betwe-en the two DBRs is a p-type AlAs layer with thickness of λ/2. Finally, one p+doped GaAs contact-layer with thickness of 0.042μm was grown.

The spectral response of the new three-cavity photodetector made in our laboratory is shown in Fig. 3. It is found that, the peak response wavelength locates at 861.4nm. Without reverse bias, its linewidth (FWHM) is about 0.95nm and its peak external quantum efficiency 17.7%. When a reverse bias voltage of 15.8V is applied, its FWHM is 1.47nm and the external quantum efficiency increases to 54.3%.

ACKNOWLEDGEMENT

This work is supported by National Natural Science Foundation of China, Project 69625101 and by Western Returned Scholars Research Foundation of National Education Committee of China and the 863 project of China.

REFERENCE

[1] M. S. Ünlü and S. Strite, "Resonant cavity enhanced photonic devices", J. Appl. Phys., vol.78, pp. 607-639, 1995.

[2] Xiaomin Ren, Joe C. Campbell, "Theory and Simulations of Tunable Two-Mirror and Three-Mirror Resonant Cavity Photo-detectors with a Built-In Liquid-Crystal Layer", IEEE J. of Quan. Electron., vol. 32, no. 11, pp. 2012-2025, 1996.

[3] Xiaomin Ren, Joe C. Campbell, "A Novel Structure: One Mirror Inclined Three-Mirror Cavity High Performance Photodetector", Technical Proceedings: International Topic Meeting On Photoelectronics (ITMPE'97), Beijing, Oct., 1997, Beijing Institute of Technology Press, Beijing, P. R. China, pp.81-84.

[4] Kai Liu, Yongqing Huang and Xiaomin Ren, "Analysis of Resonant-Cavity-Enhanced-Photo-detectors Considering the Inter-Layer Refractive Index Differences", J. of Optoelectronics • Laser, vol. 9, no. 5, pp. 360-363.

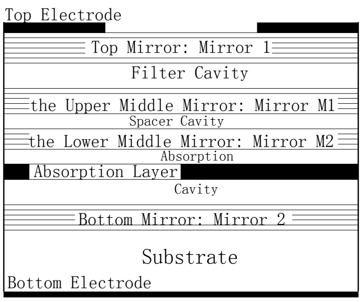

Fig. 1 Three-Subcavity Device

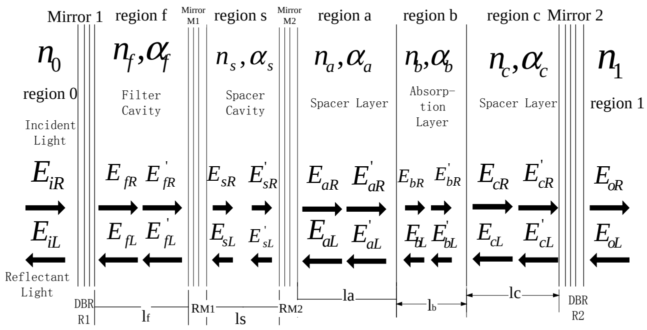

Fig. 2 Analysis Model

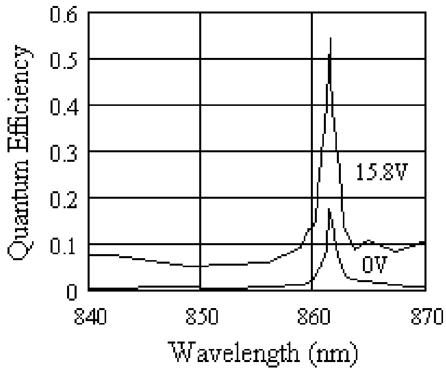

Fig.3 Quantum efficiency spectrum