Vertical-Cavity Lasers with an Intracavity Resonant Detector

Sui F. Lim, Gabriel S. Li, Student Member, IEEE, Wupen Yuen, Student Member, IEEE, and Constance J. Chang-Hasnain, Senior Member, IEEE

Abstract—We demonstrate the first intracavity quantum-well photodetector within a VCSEL for top- and bottom-emitting structures. Minimal spontaneous emission is detected by the internal detector. Dark current is on the order of picoamperes, limited by our instrument noise floor. The internal detector demonstrates high insensitivity to external ambient light as compared to an external detector. Combining various measurement techniques, we gain an understanding of such an integration and discuss the various ramifications of the issues surrounding the design, fabrication, and performance of these integrated VCSEL-detectors. This configuration facilitates flexible tailoring of the laser efficiency and the integrated detector responsivity.

Index Terms—Integrated optoelectronics, photodetectors, quantum-well devices, surface-emitting lasers.

I. INTRODUCTION

As vertical-cavity surface-emitting lasers (VCSEL’s) become more prominent in many applications, the need arises to be able to monitor the lasing power in a compact and cost-effective manner. Conventional power detection utilizes an external photodetector that usually entails bulky optical components to collimate the output light. Furthermore, an integrated detector structure is essential for simultaneous monitoring of laser arrays. Previous works have addressed this issue with a monolithically integrated pin bulk detector grown on top of a VCSEL [1], [2], though none have met all of the requirements for many applications. Specifically, from a user’s perspective, an integrated detector should detect virtually no spontaneous emission, show high responsivity to laser emission with reasonable device efficiency, receive minimal stray light, and have low dark current.

In this paper, we present experimental results of a VCSEL with an intracavity quantum-well photodetector that meets all the above requirements for the first time. By placing the quantum well detector layer at a peak of the VCSEL internal optical intensity distribution, the quantum-well resonance at only the Fabry–Perot wavelength minimizes the detection of the inherently broadband spontaneous emission. Furthermore, this resonance maximizes the detectivity of laser emission. With its embedded position, the quantum well prevents stray light from interfering with the power detection and monitoring while its thin detection region minimizes the dark current. For our experiments, we designed and fabricated two different structures: 1) a bottom-emitting VCSEL with the detector region on one side of the active region whereas the output light emerges from other side of the active region and 2) a top-emitting VCSEL with the detector region on the same side of the active layer as the output light. For both cases, we demonstrate that the photodetector response matches that of an external detector very well. Furthermore, in this paper, we will discuss the effect of wavelength mismatch between the VCSEL and the detector quantum well on the performance of the devices.

II. DEVICE DESIGN AND FABRICATION

Fig. 1(a) shows a schematic of the bottom-emitting device structure. It is comprised of n-doped distributed Bragg reflector (DBR) pairs on a GaAs substrate, followed by a 1-μm-thick InGaAs quantum wells as the active region, a p-doped DBR stack that contains two 80-Å InGaAs quantum wells as the active region, a p-doped DBR stack that contains a 3/4-thick AlAs oxidation layer for current confinement, a 5/4 spacer with one 80-Å InGaAs quantum well as the detector, and n-doped DBR pairs. The fabrication involved etching down to oxidize the AlAs layer, evaporating the top n-contact, etching down to just below the detector spacer, then evaporating an annular gold p-contact. The p-contact is used to forward bias the active region while the n-contact is used to control the voltage across the quantum-well detector. The top-emitting devices measured were designed similarly. Fig. 1(b) shows a schematic of the top-emitting device structure. The only differences were the use of an annular n-contact on top and the implementation of two oxide confinement layers—one on each side of the active region. This double oxide was used to inhibit lasing in “oxide modes” [3]. Fig. 1(c) depicts the internal intensity distribution within the top-emitting structure, showing the overlap of the active region and the detector layer with antinodes of the distribution.
III. EXPERIMENTAL RESULTS

A. Bottom-Emitting Devices

Our devices perform very well as VCSEL’s and integrated VCSEL-detectors. Fig. 2(a) shows the light versus \((I-V)\) characteristic of a bottom-emitting structure. Oxide-defined apertures are 15 \(\mu\)m in diameter, and threshold voltage is 3.3 V while threshold current is 0.9 mA, as shown in Fig. 2(b). The differential resistance of the laser is about 565 \(\Omega\), whereas the differential resistance of the internal detector is 16 M\(\Omega\) (forward bias of \(-0.5\) V for detector not shown here). The resistances are high because the doping layers have not been optimized and the contacts were unannealed. They can be further improved as discussed in Section IV. In any case, the resistance of the detector does not present an adverse effect on its function. Fig. 2(b) shows \(L-I\) traces for bottom-emitting devices as measured by the internal and external detectors for an internal detector bias of \(-0.5\) V. Both responses match closely to each other. The ripples in the \(L-I\) trace of the external detector are due to reflection at the substrate-air interface [4]. This can be eliminated with an appropriate anti-reflection coating. Note that the internal detector response to spontaneous emission is at most as sensitive as the external detector. The rather low differential quantum efficiency will be addressed in the discussion section.

In Fig. 2(c) closer inspection shows that the internal detector actually senses much less spontaneous emission below threshold than devices of previous works, where the bulk detector is integrated just outside the top DBR [1]. This feature is highly important for clear determination of threshold as well as near-threshold modulation. Effective responsivity (internal detector current/output power) is about 9 A/W, a very high value compared to that of a typical external silicon detector (\(~0.5\) A/W). Both of these attributes are results of our design—placing the quantum well detector layer at a peak of the optical intensity distribution inside the cavity.

Fig. 3 shows the bottom-emitting device \(L-I\) characteristics for different bias voltages of the internal detector. Based on observed changes in the differential quantum efficiency for detector biases above and below the detector quantum-well transparency, the absorption introduced by the internal detector is estimated to be 5.6 cm\(^{-1}\), much smaller than the total loss (sum of the mirror loss and internal loss) of 83 cm\(^{-1}\). This result agrees well with our calculation using the observed change in the threshold current. By similar calculation from experimental data, the absorption introduced by the internal detector under different biases is estimated to be 2.1 cm\(^{-1}\), also much smaller than the total loss. The losses for the bottom-emitting devices in Fig. 2 were calculated from the definition of differential quantum efficiency:

\[
\eta_d = \frac{q}{h c} \frac{dP}{dI} = \eta \frac{\alpha_m}{\alpha_m + \alpha_i}
\]

where
\[
dP/dI \quad \text{slope of } L-I \text{ trace};
\]
\[
\alpha_m \quad \text{mirror loss};
\]
\[
\alpha_i \quad \text{lumped internal loss};
\]
\[
\text{(intrinsic internal loss + loss introduced by detector).}
\]
We know $dP/dI$ from the experimental $L-I$ traces; mirror reflectivities were taken to be 99.67\% for the bottom mirror and 99.998\% for the top mirror based on our intended design. The effective cavity length was taken to be 2 \( \mu \)m. Since the intrinsic internal loss should be the same for the case where the detector is unbiased and the case where the detector is biased, calculating the fractional change in total gives the loss introduced by the internal detector alone. The loss introduced by different reverse biases across the internal detector was calculated in a similar manner. The small changes in the differential efficiency and threshold as the reverse bias across the detector is changed further demonstrates that the detector introduces little loss to the laser. Also, as shown in Fig. 3, forward biasing the detector at 2 V (above transparency of 1.2 V) introduced no significant change in the differential efficiency or the threshold. The dark current is measured to be in the picoampere range and is limited by the noise floor of our instruments, as shown in Fig. 4.

B. Top-Emitting Devices

For the top-emitting case, we see comparable performance. Fig. 5(a) shows the $L-I$ for a typical device measured by an external silicon detector. With an oxide-defined aperture of about 25 \( \mu \)m in diameter, the device has a threshold current of 5 mA. Peak output powers average about 2 mW. The threshold voltage ranges between 2–3 V whereas the differential resistance is about 200 \( \Omega \) (not shown here). Fig. 5(a) also depicts the continuous-wave (CW) responses of the external and internal detectors for a reverse bias of 1 V on the internal detector. Up to about two times threshold, the effective responsivity of the internal detector is approximately 0.8 A/W. Beyond two times threshold, the internal and external detector responses begin to diverge. In fact, Fig. 6 shows for the device under test that the effective responsivity of the internal detector rises to 2.8 A/W with increasing laser bias current and consequent red-shift of the Fabry–Perot wavelength.

To understand these characteristics, we fabricated edge-emitting lasers from the same material by etching off most of the top DBR mirrors, depositing p-contacts, and probing the devices. As shown by testing the edge-emitters, the quantum-well gain is peaked around 940 nm while the Fabry–Perot wavelength starts at 966 nm. We assume that both the active region quantum well and the internal detector quantum well are identical, as called for by our design. Since the gain peak moves faster than the Fabry–Perot wavelength as the laser pump current increases, the lasing wavelength starts at a low-respondivity portion of the quantum-well absorption curve and then effectively blue-shifts through the quantum well’s excitonic peak, inducing a nonlinear or variable responsivity.

This understanding is further verified by pulsed measurements of several devices. We used 500-ns pulses at 10-kHz repetition rate. Fig. 5(b) shows the CW optical output spectra for various pump currents of a typical device; Fig. 5(c) depicts the pulsed $L-I$ for the same device while Fig. 5(d) shows the pulsed optical output spectra. Clearly, the CW conditions induce large red-shifting in the Fabry–Perot wavelength. Pulsed operation shows that the lasing wavelength hardly shifts. In addition, the pulsed $L-I$ demonstrates that the internal and external detector responses match very well up to a much
Fig. 5. For top-emitting devices with internal detector biased at $-1 \text{ V}$. (a) External and internal detector responses for CW operation. (b) Optical output spectra for different pump currents under CW operation. (c) External and internal detector responses for pulsed operation. (d) Optical output spectra for different pump currents under pulsed operation.

Fig. 6. For top-emitting devices: Internal detector effective responsivity versus lasing wavelength (laser pump current increases with increasing wavelength).

higher pump level than for the CW case. Therefore, optimum performance can be easily achieved by careful tailoring of both active and absorbing quantum wells.

Another desirable feature of our unique integrated VCSEL-detector is its high insensitivity to external ambient light. This characteristic results from the embedded nature of the internal detector as well as the detector’s resonance at only the Fabry–Perot wavelength. Fig. 7 shows the response of the internal and external detectors for the two cases when there is no ambient light and when there is ambient light shone on the sample. Clearly, the external detector shows a significant jump in its response whereas the internal detector senses virtually none of the externally applied light.

IV. DISCUSSION

A. Design Issues

Several salient issues must be considered in regards to the optimization of these devices. First, we weigh bottom-emitting versus top-emitting structures. Common knowledge indicates that bottom-emitting devices provide feedback into themselves through reflection from the substrate. This can result in a mismatch of the external and internal detector responses as well as cause ripples in the $L-I$ traces. Furthermore, a bottom-emitting geometry for GaAs substrates does not favor emission at 850 nm and visible wavelengths, which are becoming more prevalent in use. Therefore, top-emitting geometry is most likely to be more suitable for future applications.

Secondly, we must also consider the placement of the internal detector on 1) the same side of the active region as the output light or 2) the opposite side of the active region compared to the output light. Placing the detector on the opposite side would require a very careful balance of the VCSEL mirrors’ effective reflectivities $R_1$ and $R_2$. Any imbalance would cause also an imbalance in the ratio between the output photon density and the intracavity photon density as sensed by the internal detector. Hence, this observation favors the placement of the internal detector on the same side of the active layer as the output light in order to have a matched response of the internal and external detectors.

Thirdly, the active region and detector region quantum wells must be designed in such a way that their performance provides a constant effective responsivity on the part of the internal detector. One approach would be to design the detector quantum well so that the laser Fabry–Perot wavelength lies in a relatively flat portion of the detector quantum well’s absorption response curve. This can be accomplished through, for example, tailoring individually the molar compositions of the active and detector quantum wells.

Another consideration that plays a major role in our device design is the use of oxide confinement. Without this method of carrier confinement, implementation of this geometry would be more challenging since three contacts are involved. Our devices show acceptable resistances. Variations in the oxide confinement technique as well as doping engineering can improve the voltage characteristics of our devices. Furthermore, an additional oxide layer with a different aperture can also be used to determine the internal detector’s aperture size.

B. Performance Issues

We discuss the ramifications of the four major advantages of this intracavity resonant detector integration:

Low Response to Spontaneous Emission: A low response to spontaneous emission is important for 1) a clear determination of lasing threshold; 2) a power monitor; and 3)
near-threshold modulation so that one can obtain a large signal-to-noise ratio. Previous works integrating bulk detectors just outside the top DBR have been unsuccessful because of a spontaneous emission response that is substantially larger than that of an external detector. The integrated bulk detector picks up a far larger amount of spontaneous emission than an external detector. Because of total internal reflection within the laser, the external detector senses a much smaller cone of spontaneous emission [1]. Thus, in these integrated bulk detector devices, the ratio of the photogenerated current at threshold to the photogenerated current at peak power is very high. As a result, the slope of the $L-I$ curve below and above threshold is hardly distinct, and a real-time determination of laser threshold is difficult. A device without the ability to determine threshold with high contrast renders its usefulness as a power monitor minimal. Our device circumvents this problem of integrated detectors for VCSEL’s because of the resonant nature of its detection.

High Responsivity to Laser Emission: A tradeoff does exist between the effective responsivity and the device differential efficiency since the photons detected would otherwise contribute to output or put less demand on the pump. The bottom-emitting devices showed unusually low efficiency due not only to detector absorption but more to other processing issues. The top-emitting ones, on the other hand, demonstrated 0.8 A/W effective responsivity with 16% differential quantum efficiency—reasonable quantities of performance. The key point, therefore, is that the effective responsivity and the device differential efficiency can be tailored for optimization since the effective responsivity depends on multiple parameters:

$$\zeta = \eta \left( \frac{1}{1-R} \right) \Gamma_{\text{det}} \frac{q}{\hbar \nu}$$

where

- $\zeta$ effective responsivity;
- $R$ output mirror reflectivity;
- $\Gamma_{\text{det}}$ confinement factor for detector;
- $q$ electronic charge;
- $\hbar \nu$ photon energy.

One can design the mirror reflectivity; the confinement factors for the detector layer and the active region; the placement, composition, and thickness of the detector layer; and the detector’s absorption response and overlap with the Fabry–Perot wavelength to optimize responsivity and efficiency. The high responsivity results from the fact the internal field is very high within a VCSEL. Thus, the device can be designed to perform well as a laser with the major advantages of this device integration: minimal response to spontaneous emission, very low dark current, high insensitivity to ambient light, and reasonably high effective responsivity.

The bottom-emitting devices have unusually low efficiencies. This is most likely due to growth and processing errors since these devices were the first ones fabricated. Large amounts of leakage current and high resistance caused by: 1) unannealed contacts and 2) not etching down to the correct layer for p-contact deposition are probable sources of the low efficiency. Threshold voltages (not shown in the figures) ranged from 4 to 6 V.

The top-emitting devices have adequate efficiencies (about 16%) and high responsivities (about 0.8 A/W) as shown in the figures. These devices were better grown and fabricated. Their differential efficiency is not optimum due primarily to the mismatch of the Fabry-Perot wavelength and the gain peak, as discussed in the experimental results section.

Low Dark Current: As indicated in the results, the dark current is very low for these devices. Low dark current is extremely desirable for any detection scheme.

High Insensitivity to Ambient Light: This intracavity resonant detector is highly insensitive to ambient light because: 1) it is embedded within the device and 2) its sensitivity only to the resonant wavelength renders it insensitive to the intrinsically broadband ambient light. One major application would be implementation in arrays where there is no packaging to protect the devices from ambient light. Free-space, board-to-board, chip-to-chip, and intrachip interconnects would benefit from a design that minimized the effect of ambient light on operation.

V. CONCLUSION

We demonstrated the first intracavity quantum-well photodetector integrated with a VCSEL for both top-emitting and bottom-emitting structures. By taking advantage of the quantum well resonance at only the Fabry–Perot wavelength and the strategic placement of the detector quantum well at an optical intensity peak, we achieved reasonably high effective responsivity as well as low spontaneous emission detection by the internal detector without adversely affecting the laser performance. Furthermore, this combination of features renders the internal detector highly insensitive to external ambient light—a characteristic that is very desirable in any laboratory or commercial application. Based on our understanding of the behavior of the devices, we anticipate optimization in the near future.

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REFERENCES

Sui F. Lim was born in California in 1968. She received the B.S. degree in physics (summa cum laude) from the University of California at Davis, in 1991 and is working toward the Ph.D. degree at Stanford University under the direction of Dr. C. J. Chang-Hasnain, Professor at the University of California, Berkeley.

Her research focuses on integrated VCSEL-detectors, self-pulsating VCSEL’s, indirect VCSEL modulation, and broadband VCSEL amplifiers.

Gabriel S. Li (S’93) was born in Hong Kong on September 1, 1970. He received the B.S. degree in applied mathematics, engineering, and physics (with honors) from the University of Wisconsin-Madison, in 1991 and is currently working toward the Ph.D. degree in applied physics at Stanford University, Stanford, CA.

His current research interests are focused on the MBE growth, fabrication, and design of optoelectronic devices, including vertical-cavity surface-emitting lasers and micromechanical wavelength tunable devices.

Wupen Yuen (S’91) was born in Tainan, Taiwan, R.O.C., on August 20, 1969. He received the B.S. degree in electrical engineering from the National Taiwan University in 1993 and the M.S. degree in electrical engineering from Stanford University, Palo Alto, CA, and is currently working toward the Ph.D. degree in the Department of Electrical Engineering, Stanford University.

From 1991–1993, served with the Chinese Air Force. His current research interests include the design, fabrication, and MBE and MOCVD growth of multiple-wavelength VCSEL arrays and other novel VCSEL structures. He has authored or co-authored more than 35 papers and one book chapter.

Constance J. Chang-Hasnain (M’88–SM’92) was born in Taipei, Taiwan, R.O.C., in 1960. She received the Ph.D. degree in electrical engineering and computer sciences from the University of California at Berkeley in 1987.

From 1987 to 1992, she was a Member of the Technical Staff at Bellcore, Red Bank, NJ. From April 1992 to September 1995, she was an Assistant Professor and from September 1995 to December 1995, she was an Associate Professor in the Electrical Engineering Department, Stanford University, Stanford, CA. Since January 1996, she has been Professor of Electrical Engineering and Computer Sciences at the University of California at Berkeley.

Her current research interests include semiconductor optoelectronics devices and their applications. Her research topics include 2-D VCSEL arrays, micromechanical tunable VCSEL and detectors, self-pulsating and intracavity modulated VCSEL and their system applications. She has published over 70 refereed journal articles, been awarded eight patents, and contributed three book chapters. She has also presented over 60 invited talks in conferences, universities, and industry.

Dr. Chang-Hasnain has served on technical program committees for a number of conferences including CLEO (Conference on Lasers and Electro-Optics), OFC (Optical Fiber Communications), International Semiconductor Lasers, Conference, Frontiers of Engineering sponsored by the National Academy of Engineering, IEEE Lasers and Electro-Optics Society (LEOS) Annual Meeting, OSA Annual Meeting, etc. She was the Conference Chair for High-Speed Optoelectronics Conference ’96, Program Co-Chair for CLEO’97, and will be the Conference Co-Chair for CLEO’99. She was a member of the IEEE LEOS Board of Governors from 1992 to 1995 and LEOS Editor of the IEEE Circuits and Devices Magazine. She was awarded the 1991 Outstanding Young Electrical Engineer Award from Eta Kappa Nu. She was named the Presidential Faculty Fellow, National Young Investigator, David and Lucille Packard Foundation Fellow, and the Alfred P. Sloan Research Fellow. In 1994–1995, she received the IEEE LEOS Distinguished Lecturer Award. She is a Fellow of the Optical Society of America.