Oscillation wavelength shifts observed in vertical cavity surface emitting lasers exposed to magnetic fields

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ABSTRACT

Even as long ago as the 1960's, scientists understood that diode lasers' oscillation wavelengths demonstrated significant shifts to the shorter wavelength side, when subjected to strong magnetic fields, at extremely low temperatures. When we exposed Fabry-Perot type diode lasers oscillating at 780 nm to weak magnetic fields, at room temperature, the oscillation wavelength was observed to have shifted to the longer wavelength side. In discussions of shift mechanisms aimed at explaining how/why our results differ from those obtained in studies conducted in the 1960's, we noted a rise in temperature and an increase in the carrier density, and how it affected the characteristic shifts observed, when a magnetic field was applied to the Fabry-Perot type laser diodes parallel to the injection current. In the present work, we tested the oscillation wavelength shift of a vertical-cavity surface-emitting laser (VCSEL) in a magnetic field, because we expected that, by doing so, the VCSEL would show a shorter wavelength side shift.

Keywords : VCSEL, magnetic field, wavelength shift

1. INTRODUCTION

Much attention has been focused on diode lasers' oscillation wavelengths' susceptibility to fluctuations in injection current and temperature, among other things. As long ago as the 1960's, scientists were testing to see what, if any, changes might result, by exposing them to magnetic fields of varying strengths[1-5]. At that time, they observed oscillation wavelengths shifting to the shorter (high frequency) side, at extremely low temperatures (< 80 K) and strong magnetic fields (< 4 T).

Fully aware of their accomplishments, we exposed a 780nm Fabry-Perot type diode laser (F.P. laser) to a weak magnetic field (<1.4 T), at room temperature (300 K). The oscillation wavelength shifted to the low frequency side[6-9] due to temperature rises in the active region stemming from the electromagnet and the laser's resistance. The decrease in optical output power and increase in laser-voltage confirmed our theory that wavelength-shifts occurred as the direct result of temperature rises. But, they also demonstrated that the speed at which this effect occurs is far too slow, in real-world applications.

In this work, we focus our attention on the wavelength shift brought about by the change in the VCSEL's current flow at room temperature, when the device is exposed to a magnetic field. When we applied a weak magnetic field parallel to the direction of current flow, carrier-density increased in the active region, producing a shift to the shorter wavelength side; a result that differs significantly, from the one we obtained in previous experiments using the Fabry-Perot diode laser. These adjustments improve the VCSEL's performance, without altering its structure.

2. EXPERIMENTAL SETUP AND METHODS

In Figure 1, which shows the orientation of the magnetic field, magnetic flux-density vector $\boldsymbol{B}$, and normal direction $\boldsymbol{n}$ of the laser diode's layered surface are set (a) parallel to one another ($\boldsymbol{B}//\boldsymbol{n}$) and (b) perpendicular ($\boldsymbol{B} \perp \boldsymbol{n}$). There is great variety, in the way laser diodes' inner structures align themselves ($\boldsymbol{I}$ and $\boldsymbol{n}$). We define the direction of $\boldsymbol{B}$ by its relation to $\boldsymbol{n}$. The observed results indicated that, only in cases where $\boldsymbol{B}//\boldsymbol{n}$, did the laser's oscillation wavelength actually shift.

Physics and Simulation of Optoelectronic Devices XX, edited by Bernd Witzigmann,
Marek Osinski, Fritz Henneberger, Yasuhiko Arakawa, Proc. of SPIE Vol. 8255, 825522
 · doi: 10.1117/12.908016

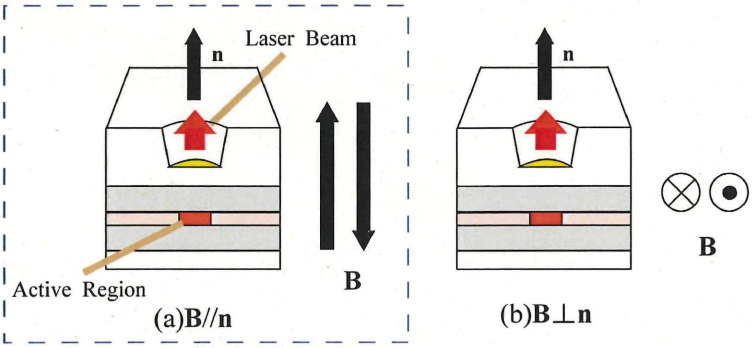


Fig. 1 Orientation of the magnetic field

Figure 2 shows the monochromator-based setup used to observe the oscillation wavelength shift. In these tests, we used a single-lateral mode VCSEL oscillating at 850 nm.

When an electromagnetic field is applied to the VCSEL oscillating at 850 nm, a mirror reflects the resulting output to the monochromator. The VCSEL beam travels along an optical fiber, arriving at a monochromator boasting 0.04 nm resolving power. Thereafter, it is introduced to a data logger by means of a Photomultiplier Tube (PMT). Because the sweep-rate of a monochromator is 0.02 nm per second, the measurement requires a few minutes, in total. Although the VCSEL temperature is controlled within1/100 K, it is influenced, somewhat, by the heat of the electromagnet.

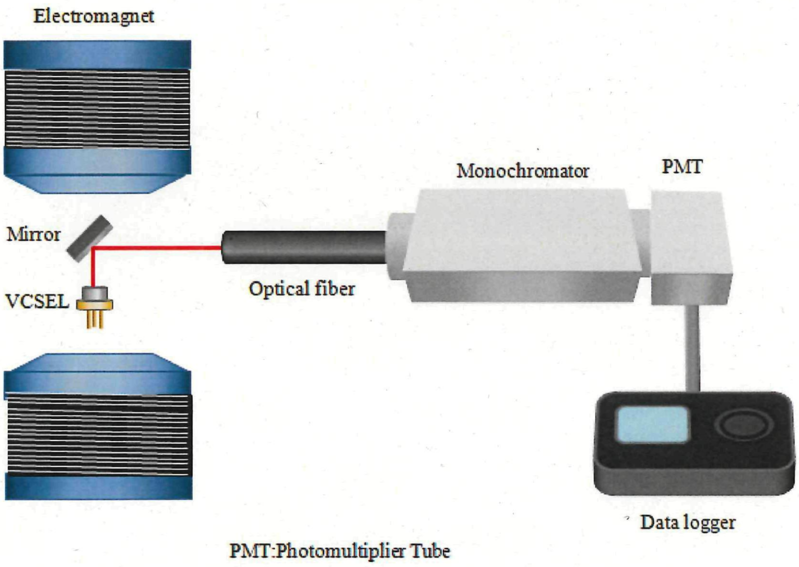


Fig. 2 Experimental setup using a monochromator

Figure 3-1 details our observations of the oscillation wavelength shift, using a beat note between a sample VCSEL (VCSEL1) and a reference VCSEL (VCSEL2). While VCSEL1, which oscillates at 850 nm, was exposed to a magnetic field by an electromagnet, we measured the VCSEL1's frequency shift, by observing the beat note between the oscillation wavelengths of VCSELs 1 and 2. The beams, guided by separate sets of mirrors through a beam splitter (BS), follow the same optical path to an avalanche photo diode (APD). Once the optical setup is properly aligned, the APD's output signal is introduced to the spectrum analyzer, where it is detected as a beat note that reveals the degree to which the two frequencies differ. Any fluctuation in this beat note, after the magnetic field has been applied to VCSEL1, indicates a shift in the wavelength, i.e., in the oscillation frequency. Because the VCSEL's temperatures are controlled within 1/100 K, and all measurements are completed within a few seconds, the heat generated by the electromagnet exerts no discernable influence on the VCSEL.

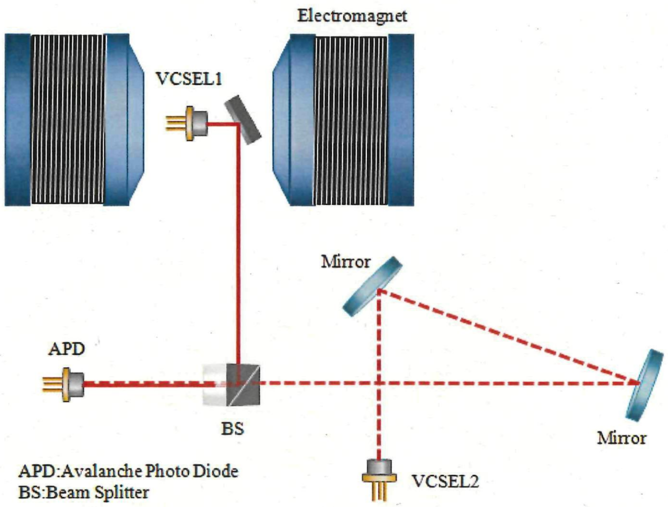


Fig. 3-1 Experimental setup using a beat note (VCSEL-VCSEL)

Figure 3-2 describes the optical system observing the beat signal between VCSEL and F.P. type diode laser. We replaced the reference VCSEL2 (which is not influenced by magnetic fields), with an F.P.-type LD, significantly improving resolution, in the process.

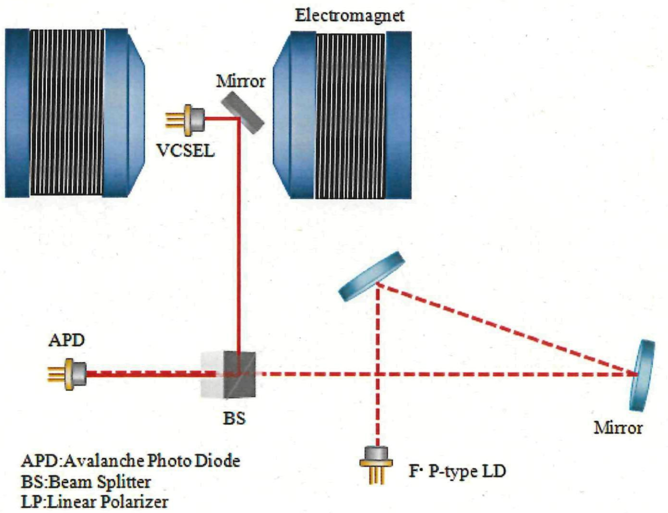


Fig. 3-2 Experimental setup using a beat note (VCSEL-F.P. type LD)

3. RESULTS

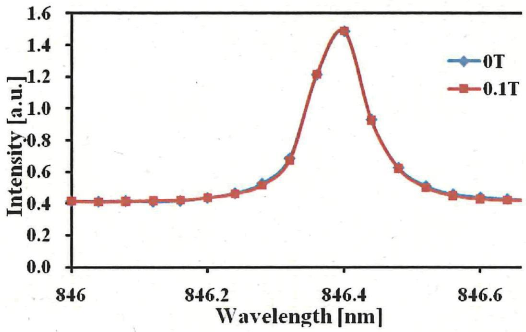
3.1 Wavelength shifts in experiments using a monochromator

Figure 4 demonstrates the results of experiments in which we used a monochromator to measure oscillation wavelength shifts. The vertical axis shows the optical output power observed by a PMT, and expressed in a.u., while the horizontal axis shows the wavelength, measured in 0.01 nm increments, by the monochromater's built-in stepping motor. The VCSEL's temperature was maintained at 298 K, (±1/100 K).

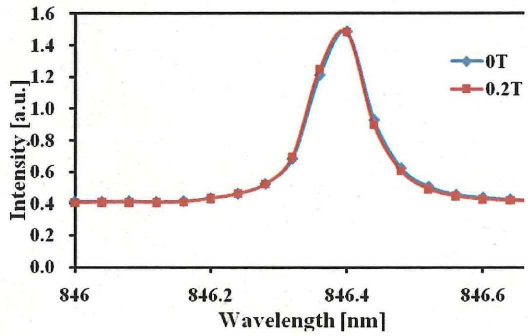
3.1.1 Results of a single-lateral mode VCSEL in a magnetic field

As shown in Fig. 4, no shift in frequency was noted, when magnetic fields ranging from 0.1~ 0.3 T were applied. At 0.4

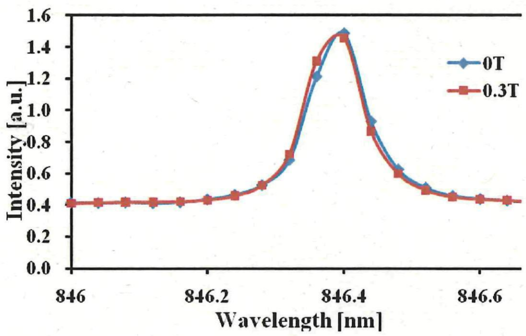
T and above, however, we observed a short wavelength side shift. And, while we expected a considerable amount of increase in optical output power, due to the magnetic field, there was actually very little, at 0.4 and 0.5 T. Injection-current flow to the VCSEL was 2.8 mA.



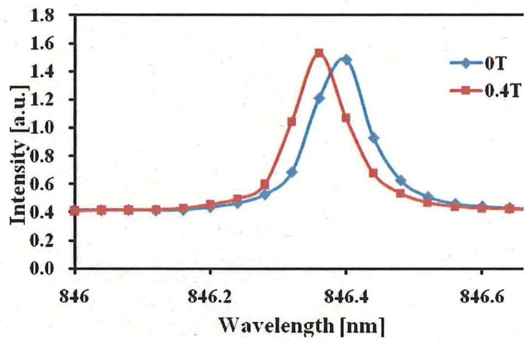
(a)B=0.1T



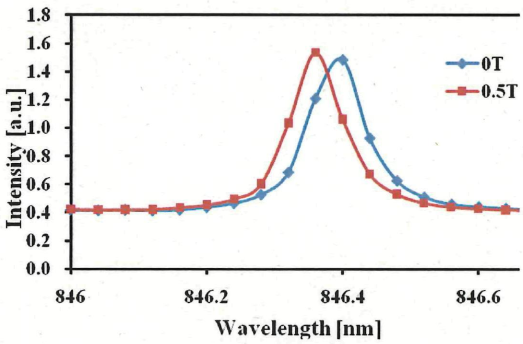
(b)B=0.2T



(c)B=0.3T



(b)B=0.4T



(d)B=0.5T

Fig. 4 Experimental results by a monochromator

3.2 Wavelength shifts in experiments involving a beat note

Figures 5 and 6 detail the spectrum observed using the beat note. We were able to check the wavelength shift by observing the spectrum of VCSEL in a monochromator. However, the wavelength shift below resolution was indistinguishable during monochromator-based tests. We therefore decided to observe the wavelength shift using a high-resolution beat signal between sample- and reference- laser beams. Injection-current flow to the VCSEL was 2.0 mA and to the F.P. type LD was 90 mA.

3.2.1 Observed frequency shift using a beat note (VCSEL-VCSEL)

We have tried to observe frequency shifts, using the beat-note between sample- and reference- VCSEL frequencies (Fig. 5). But, beat-signal width is too great, to measure the wavelength shift correctly, because the oscillation width of each VCSEL is wide, and because the influence of changes in current-flow to the VCSEL are slight, compared with the influence of ambient noise.

3.2.2 Observed frequency shift using a beat note (VCSEL-F.P. type LD)
We have tried to observe frequency shifts, using the beat-note between a sample VCSEL and reference F.P. type diode laser frequencies (Fig. 6). This means that the oscillation linewidth of this beat signal (VCSEL- F.P. type diode laser) is narrower than that of shown in Fig. 5. As a result, a frequency shift of approximately 1.2 GHz has been observed by increasing a magnetic field to 0.5 T (Fig.7).

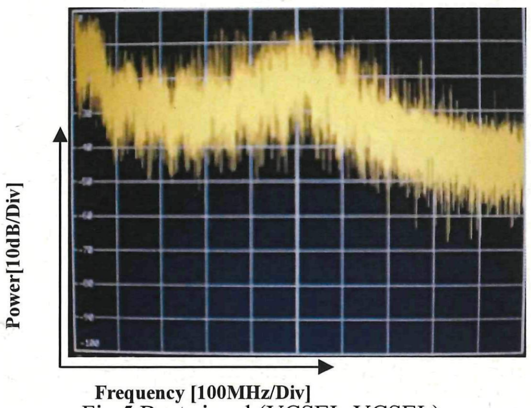


Fig.5 Beat signal (VCSEL-VCSEL)

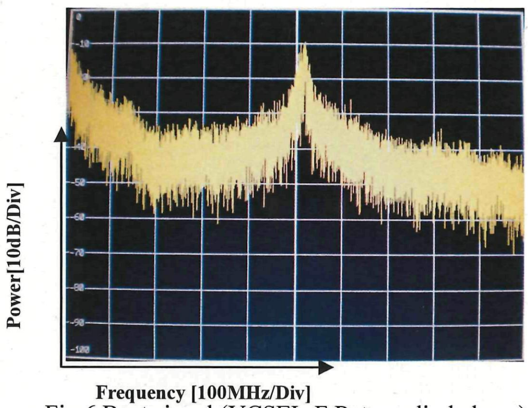


Fig.6 Beat signal (VCSEL-F.P. type diode laser)

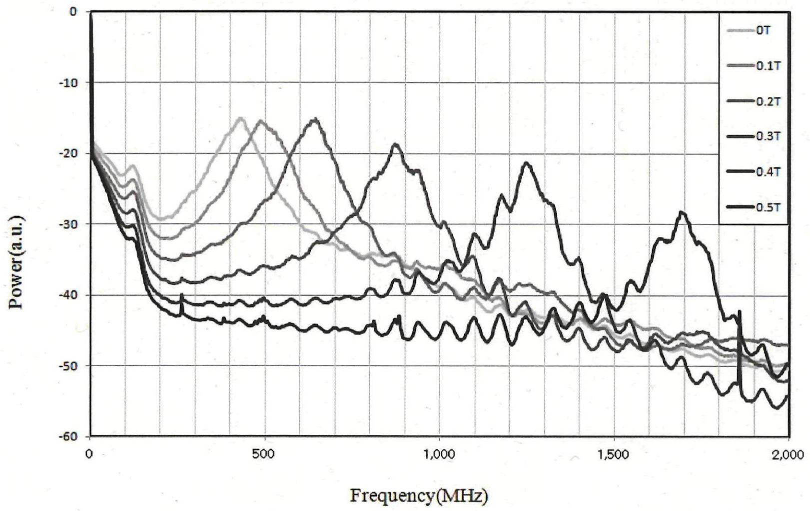


Fig.7 Frequency shift observed using a beat note

4. DISCUSSION

4.1 Discussion of wavelength shift in case of using monochromator

Figure 4 shows how the VCSEL's oscillation frequency shifts to the short wavelength side, when exposed to a magnetic field, due, we believe, to the magnetic field's boosting carrier density in the active region of the VCSEL, which then results in a short wavelength side shift. This outcome is quite unlike the results obtained, when we used F.P. type laser diodes. Although a magnetic field of less than 0.3T was unable to bring about a wavelength-shift, one greater than 0.4T shifted it to the short wavelength side, with relative ease, due, we believe, to the fact that wavelength shifts in weak magnetic field do not exceed the resolving power of our monochromator. However, as shown in Fig.4 (d), we could only prove that the wavelength had, in fact shifted, when subjected to the magnetic fields greater than 0.4T. Because we wanted to observe this shift quantitatively, we simply relied on a beat signal between two laser beam frequencies.

4.2 Discussion of wavelength shift in case of using beat note

Figures 5, 6 and 7 show the experimental results using a single-lateral mode VCSEL. The shorter wavelength i.e., higher frequency side shift was observed at ***B//n*** in this setup, too (Fig. 4). We understand only too well, the difficulty of observing a wavelength shift from VCSELs beat signal (VCSEL-VCSEL) (Fig. 5), due to the excessive width of the beat signal. Then, we use F.P. type diode laser, which has the narrow oscillation linewidth, as a reference laser. By replacing the reference laser, we have the narrow beat signal shown in Fig. 6. Figure 7 shows the frequency shift observed using the beat signal in Fig. 6. About 1.2 GHz shift has been observed at 0.5 T magnetic field.

The frequency of the sample VCSEL was set at the shorter wavelength side from that of the reference F.P. type laser, after which we applied the magnetic field, so Fig. 7 shows that the oscillation frequency of our sample VCSEL shifts to the higher frequency side.

Our monochromator is capable of operating at 0.04 nm resolution; roughly 20 GHz, at 850 nm. However, as the experimental results shown in Fig. 7 indicate, such large shifts are seldom observed. And, since it uses a stepping motor to power changes in wavelength, we believe that we observed a beat-signal shift, in a critical area.

4.3 Lorenz force's effect on current-flow in VCSELs

We believe magnetic fields affect current-flow within- and around- an active layer. Figure 8 shows how the Lorentz force alters current flow. Figure 8 (a) gives a side-view of a laser diode, and its current flow in $\boldsymbol{B} \perp \boldsymbol{n}$ direction. When we applied a magnetic field, no shift in frequency was evident.

We obtained the desired frequency shift, only when we applied the magnetic field parallel to direction ***n***. Figure 8 (b) shows the overhead view of a laser diode and its current flow in ***B//n*** direction. In this case, the Lorentz force alters the flow of the outward-bound current, and subsequently reduces the diffused current. So, current- (i.e.: carrier-) density will increase, resulting in higher-side shifts in oscillation frequency.

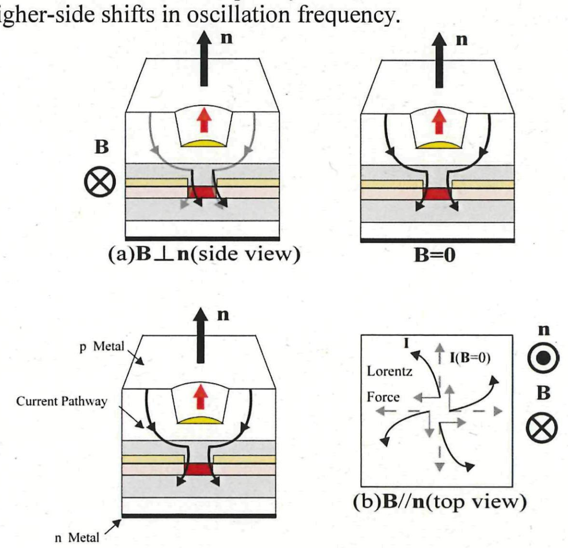


Fig. 8 Change of the current flow by Lorenz force

5. CONCLUSION

Through the use of a monochromator (Fig. 4), we measured the VCSEL's oscillation frequency, shifted in a magnetic field to the short wavelength side (high frequency side). First, we tried to observe this frequency shift, using the beat-note between sample- and reference- VCSEL frequencies. This could not be accomplished, in experiments using the beat-note, because VCSELs' oscillation linewidths are too wide to distinguish frequency shifts of <1 GHz. Then, we attempted to observe this frequency shift, using the beat-note between sample VCSEL and reference F.P. type laser frequencies. In the end, a shift of about 1.2 GHz was achieved, by increasing the magnetic field to 0.5 T.

ACKNOWLEDGMENTS

This work is supported in part by a Grant-in-Aid for Scientific Research (No.22560035) from the Japan Society for the Promotion of Science.

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