Chapter 1

Everyone Uses Surface Emitting Lasers

- The internet is a priming agent.
- Mass produced in computer mice, laser printers, smartphones, and other electronic devices.
- Also found in cars.
- They are the basic light-emitting devices that support AI and the IoT.

1.1 The Trigger

- The explosive development of the internet

Around 1999, the internet spread rapidly worldwide. Around that time, mass production of “surface emitting lasers” began. It is called a VCSEL (vertical cavity surface emitting laser), after a pixel, and it refers to a small device such as a transistor that constitutes a semiconductor large-scale integration (LSI). Figure 1.1 shows a model of a 2D array of surface emitting lasers.

![Figure 1.1](image)

**Figure 1.1** The concept of an array of 2D surface emitting lasers.
1.4 Applications of Surface Emitting Lasers and New Application Fields

Products incorporating surface emitting lasers began to appear on the market around 2000, and these systems were called VCSEL photonics. Incidentally, photonics is a field where light (photo-) and electronics (-nics) are fused. The application field is shown in Fig. 1.6, and the details will be described in Chapter 11.

Figure 1.5 Surface emitting laser in a 5-mm-diameter “CAN” package for a computer mouse: the laser is from Ulm Photonics GmbH (now Philips Photonics GmbH), Germany, with the device in the center.

Figure 1.6 Applications of surface emitting lasers.
Chapter 2
Surface Emitting Lasers: From Horizontal to Vertical

- Let’s make a vertical thing and make it thin.
- Mission impossible!
- How are surface emitting lasers and LEDs featured?

2.1 Horizontal to Vertical

The author created a vertical cavity surface emitting laser (VCSEL), as shown in Fig. 2.1(a), on March 22, 1977 {1977 IGA}. In a conventional semiconductor laser, light reciprocates in the lateral direction and resonates by the light-emitting region laid in the horizontal direction, as shown in Fig. 2.1(b) {2018 SUE}.

Although the horizontal length is as small as 0.3 mm, it is still 300 times as large as the light wavelength of 0.001 mm. Therefore, analogous to a musical instrument, many harmonics appear, and the spectral purity of the light is lost. As will be described in detail later, this horizontal cavity laser (abbreviated as a stripe laser) could not be manufactured by a monolithic process by thin film formation such as a semiconductor large-scale integrated (LSI) circuit.

Figure 2.1 Resonator of a semiconductor laser: (a) vertical cavity surface emitting laser, and (b) horizontal cavity stripe laser.
emission of radiation,” which literally represents “amplification of light by stimulated emission.”

Analogous to the so-called “howling” that occurs when the sound of the speaker enters a microphone, at a certain wavelength, a phenomenon called “oscillation” occurs wherein the light that leaks out of the reflector is balanced with the light that is amplified. This is laser oscillation, and as shown in the left image of Fig. 2.7, the light of a specific wavelength comes out in the form of a beam. Although the laser was a concept of “amplifying action,” it was the name for the device that oscillates (hence the -er suffix). The light beam from an actual surface emitting laser was shown in Fig. 1.3.

Since no resonance occurs in LEDs, the wavelength of light emitted from the active layer is broadened, as is the light emission. It is rather convenient for lighting. A major feature of the laser is that the spread width of the wavelength is small (in terms of the spectrum, it is narrow), and beam-like light is obtained. This is an essential property of optical fiber communication and optical disks. The properties of the two are organized and shown in Table 2.2 along with their uses.

![Figure 2.7](image-url) Difference between a surface emitting laser and an LED, shown as a diagram and a picture of the device in the package.

**Table 2.2** Difference between a surface emitting laser and LED and usage

<table>
<thead>
<tr>
<th>Nature</th>
<th>Surface Emitting Laser</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>Narrow</td>
<td>Wide</td>
</tr>
<tr>
<td>Light output</td>
<td>Beam shape</td>
<td>Spreading</td>
</tr>
<tr>
<td>Interference</td>
<td>Large</td>
<td>None</td>
</tr>
<tr>
<td>Focusing of light</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Applications</td>
<td>Optical communication</td>
<td>Lighting, lamp</td>
</tr>
<tr>
<td></td>
<td>Optical disk</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3
My Research: Started from a Ruby Laser Experiment

- Learning from Maiman’s experiments.
- The impression that shines brightly.
- The feeling of a good laser.
- It provided a glimpse of the surface emitting laser.

Chapter 2 described the principle of surface emitting lasers and the differences from stripe lasers; the invention of Japan’s three verticals in 1977; and the differences from LEDs. In this chapter, we will touch on the emergence of the lasers themselves behind the idea of surface emitting lasers.

3.1 The Appearance of the Laser

- Ruby laser

The first appearance of the laser in 1960 started with pulsed operation. Theodor Maiman’s breakthrough idea realized the first laser on May 16, 1960 in the laboratory of the airline company Hughes in California (scoring a point on the physicists on the east coast of the United States) {1960 MAI}. Others who were researching lasers (or rather optical masers) had in mind coherent light with a stable continuous oscillation.

It may be because the microwave maser has served as a frequency standard. Ruby’s fluorescence had been studied, and therefore its application to continuously operating lasers was considered, but it was difficult. Maiman succeeded in lasing it with a pulse-like excitation for a moment. The transformation of ideas that break assumptions can bring great innovation to the world at any time. The success of this ruby laser oscillation led to the rise of optoelectronics centered on the laser.

Maiman’s name was noted for the laser’s inventor when his boss, Harold Lyons, decided to make a press release the day after the experiment’s success,
invention of surface emitting lasers. Both the ruby laser and the surface emitting laser consist of a resonance comprising two reflectors. After the ruby laser experiment, I read articles published by Bell Labs in every corner, including a paper on laser resonators by H. Kogelnik and T. Li. I did not imagine I would later go to Bell Labs and owe these people a great scientific debt. Regardless, it may be said that the feeling of the laser came to be well understood.

- Graduate school doctorate

At that time, it was natural for seniors and classmates to go to graduate school and study. In my Master’s program, I continued to study the ruby laser. I was to enter the doctoral course with Tetsuhiko Ikegami (ex-NTT/ former Aizu University president) during the same period, but I felt mentally fatigued when I finished writing my Master’s thesis. I felt the lack of technical knowledge. When I entered the doctoral program under such conditions, Prof. Suematsu asked, “What do you think about the theme of the doctoral program?” Also he advised, “The ruby laser is already being put to practical use by NEC and other companies. It would be a good idea to pursue some other idea.” Since Ikegami worked on semiconductor lasers, I decided to change the theme, following the suggestion that optical transmission seemed development in the future.
Chapter 4
The Very Beginning is the Most Important Part: Well Prepared, No Regret

- Let’s make a laser with a semiconductor.
- Izuo Hayashi’s semiconductor-laser room-temperature continuous operation made a big impact.
- The first step is important, and preparation should be complete.

4.1 Inspiration for Semiconductor Lasers

- Continuous temperature operation of a semiconductor laser at room temperature

Around 1970, the operation of semiconductor lasers that emit continuous light at room temperature was performed at Bell Labs by Izuo Hayashi and Morton B. Panish {1970 HAY}, independent of the results in the Soviet Union achieved by Zh. I. Alferov and coworkers {1969 ALF}. This was achieved by a method of forming gallium arsenide (GaAs) and gallium aluminum arsenide (GaAlAs), to which aluminum was added by crystal growth. In the fall of that year, Dr. Hayashi visited the Tokyo Institute of Technology by the invitation of Prof. Suematsu and gave a talk on the experimental results. The crystal growth of the “double heterostructure,” which is a sandwich structure of GaAlAs/GaAs /GaAlAs, performed by co-investigator Panish was excellent. The heterostructure was patented by Herb Krömer in 1962 {1963 KROa, 1963 KROb}, and he was awarded the 2000 Nobel Prize in Physics for it. Most researchers were not aware of this patent. The demonstration by Hayashi and Panish showed the effectiveness of the double heterostructure, which revealed Krömer’s idea to the world.
Anecdote 4a: Optical Fiber Communication

Q (Chief Editor): In the field of optoelectronics, what was the situation like in 1977, when you invented the surface emitting laser?

A (Iga): In the infrared region of the 1.3-μm-wavelength band, there was the prospect that the transmission loss of optical fiber would be extremely small. Eventually, the reliability of semiconductor lasers and silica-based optical fibers using gallium indium arsenide phosphide (GaInAsP), which appears in this book, was secured, and optical communication became practical. After that, it was found that the transmission loss became lowest in the 1.55-μm band, and the submarine cable was installed around 1990.

Q (Chief Editor): After that, did the internet come out?

A (Iga): The internet has exploded since 1995, and optical fiber communication networks have supported it. The surface emitting laser began to be used in a short-distance LAN.

Q (Chief Editor): The industries that use networks are widespread.

A (Iga): Therefore, we needed a data center to accommodate large-scale Big Data. There was no way to use electrical cables to get information into and
Chapter 5
The Birth of the Surface Emitting Laser: A Difficult Delivery

- Why was there a surface emitting laser?
- Think until you feel the mission.
- Only a fine line between new and odd.

5.1 Research Mission

Room-temperature continuous operation at new wavelengths, power increases, reliability, etc. were the main topics (see Fig. 5.1). Companies focused on solving these problems and putting them to practical use. Around 1977, I was dissatisfied with the previous lasers while studying long-wave semiconductor crystal growth and devices. In most lasers, the reflector is made by cleaving the crystal. Instead, our problem was, “Can it be made by process technology such as a large-scale integrated (LSI) circuit?” This is called monolithic manufacturing.

Another problem was that if optical fiber communication cannot operate at a single wavelength, propagation over a long distance causes a difference in propagation time due to the difference in wavelength, and the optical pulse spreads. This problem is called wavelength dispersion.

Also, when many wavelengths are packed into an optical fiber in the future, channels will be mixed up due to differences in wavelength. The wavelength must be secured by the laser. This is called wavelength reproducibility, which involves two issues: whether the same wavelength can be reproduced well or if the desired absolute wavelength can always be produced.

Distributed feedback (DFB) lasers and etched mirror lasers are candidates for lasers that can be fabricated monolithically. The DFB laser uses a
strongly recommended that it be adopted. It was reported at the LED Symposium in March of 1978, and this was the first oral presentation of the idea at an international conference [1978 IGAb].

5.3 Let’s Make a Surface Emitting Laser

Next, as a research strategy I considered the following items:

1. Making the necessary crystal growth equipment,
2. Making a reflector with high reflectivity, and
3. Considering a structure that enables wavelength control.

Along with these strategies, a surface emitting laser was made for the first time using materials of GaInAsP in 1978. Figure 5.4 shows the device. Haruhisa Soda, who advanced to the doctoral course, made it. On the InP substrate described above, a double heterostructure is grown with GaInAsP as an active layer. Light is emitted by injecting current from circular electrodes, and metal reflectors are formed above and below the substrate to form a resonator [1979 SOD].

This first laser was driven by a pulse current, cooling at a temperature of 77 K with liquid nitrogen. The threshold was also very high at 800 mA and more than 20 times that of a normal laser, and it was out of order immediately.

When we looked at the light coming out of the device, it flashed rapidly at a certain current. Furthermore, it was possible to finally take the spectrum, and it was found to be much narrower than ordinary LEDs, which again was to be a laser oscillation. As mentioned above, the name was given as “surface emitting laser,” according to the advice of Prof. Yasuharu Suematsu.

Figure 5.4 The first surface emitting laser (1979 SOD).
Chapter 6
Bell Labs: Experiencing the Major League

- An overseas researcher in the United States.
- Bell Labs as the best research environment.
- Bell Labs as the major league in terms of excellent scientists.

6.1 An Overseas Researcher in the U.S.

In 1979, I went to study abroad under the sponsorship of the Ministry of Education. I decided to stay at Bell Labs of the United States and MIT (Massachusetts Institute of Technology). All told, I chose to study at Bell Labs for about a year and a half.

When I first realized a surface emitting laser, everyone around me thought it was the time to accelerate the research. Sometimes, I was asked, “Why did you go to Bell Labs in that circumstance?”

I think that I was not hasty at that time. For example, there were only a few institutions that studied surface emitting lasers, such as Tohoku University and the National Electro-technical Laboratory, and of course there was little momentum around the world. My laboratory was well-equipped, and a number of Ph.D. students were working. I could say that I thought that research would somehow proceed. Besides, the opportunity to be an overseas researcher provided by the Ministry of Education was truly difficult to obtain, and I thought that it would be wasteful to miss it. Through this program, I was able to afford a one-year stay and round-trip air travel. (Of course, because $1 was about 260 yen, the fellowship I received in Japanese yen went down when going to the United States and converting into dollars.) After a while, during the time of Prime Minister Tanaka Kakuei, this support was shortened to 10 months. This is a serious change. Why? Because to live in a foreign country with your family, you need to stay for a year throughout the season, or you will not appreciate its qualities. Most likely,
Chapter 7
Continuous Operation at Room Temperature: Mission Impossible

- Presentation at a conference: everyone thought it was an impossible goal.
- Thin-film surface emitting laser: a large breakthrough.
- Aiming for room-temperature continuous operation of a surface emitting laser.
- The problem is technology.
- Room-temperature continuous oscillation succeeded.

7.1 Reputation and Understanding of Surface Emitting Lasers

I mentioned earlier that I presented a paper on the surface emitting laser at the Quantum Electronics International Conference (IQEC) in Boston in June 1980. At that time, Yu. M. Popov of the Soviet Union came to me and told me that this device would have a future. He, Nobel Laureate winner N. G. Basov, and others had been working on a semiconductor-film laser with electron beam pumping. Others seem to have thought, “Oh, it is interesting, but I don’t know if it will become something or not.” Even after the international conference ended and I returned to Bell Labs, most people thought that it would not work in the future. T. P. Lee, who later became the director of the NSF, was one of them, though later he said that his perception was incorrect. He eventually edited and published a book on surface emitting lasers.

At Bell Labs, there was only one person who made a positive evaluation: Mike Duguay, who later became a professor at Laval University in Canada. He also induced me to debate, saying, “I am against Japanese whaling and tried to bring sunlight into the room to save electricity.”
7.4 Low-Threshold Surface Emitting Laser: Surpasses Lasers for CD

On the other hand, optical disks (compact disks, CDs) began to appear in 1982, and the short-wavelength laser would be considered once more. We decided to start the crystal growth of gallium arsenide (GaAs) again and set up another liquid phase epitaxy (LPE) growth furnace. Prof. Toshiharu Tako of the same department retired; Katsumi Kishino, who was a research associate, transferred to become an associate professor at Sophia University; and it was decided to accept the doctoral student Susumu Kinoshita. Kishino reached retired from Sophia University in March 2018. I heard in his final lecture at that time that LPE was said to be handmade by Kishino and Kinoshita.

It has become commonplace now, but I thought that it would be important to stack semiconductor heterostructures into multiple reflectors, and I was trying it the first time in the world. An initial attempt was posted to an international conference. When a company committee member told me that “I could do it immediately with MBE,” I felt very disappointed. In truth, it might be possible with molecular beam epitaxy (MBE), etc.; however, since the laboratory was small and there was only a limited budget at that time, we had to rely on liquid phase growth. I was irritated since I knew such thing was possible, but the budget could not make it possible.

In the liquid phase growth reactor, GaAs has become better than the long wavelength as a surface emitting laser. The first buried-structure surface emitting laser has a threshold current of 6 mA at room temperature. Since the threshold was about 50 mA in lasers for CDs of those days had a low threshold, opposed to normal lasers in surface emitting lasers. The result is presented as a post-deadline paper of the International Semiconductor Laser Conference held in Kanazawa in 1986 {1986 IGA}. And everyone seemed surprised that the characteristics were quite good.

7.5 Homemade Vapor Deposition System

In order to fabricate a surface emitting laser, it is necessary to make the surface emitting laser flat and to form a very thin semiconductor layer. In the liquid phase growth apparatus described in the previous chapter, although the crystallinity is good, it is difficult to flatten the surface of the final layer, and it is difficult to alternately apply thin films of different compositions.

After all, it was judged that flat crystals could not be obtained without vapor phase growth. Speaking of the first half of the 1980s, the vapor phase growth apparatus and the molecular beam growth apparatus were still in the testing stage, expensive (with a cost of more than tens of millions of yen), and unlikely to be available in small laboratories. We could not sit still and had been trying to introduce MOCVD equipment involving Kazunori Moriki, who was a research associate at that time. This system was also designed by
Chapter 9
The Berlin Wall Collapse: The Great Research Competition in the 1990s

- Bell Laboratories also achieved continuous operation.
- Fall of the Berlin Wall.
- Role of DARPA.
- Intensified development competition in the 1990s.
- Is a surface emitting laser a destructive technology?
- Research and development of surface emitting lasers in Japan.
- Guest professor at the University of Ulm.
- MEXT COE program.

9.1 Also at Bell Labs
In the author’s group, quantum wells were tried in surface emitting lasers around 1986, but we did not achieve low thresholds at that time. Jack Jewell and colleagues made low-threshold surface emitting lasers in 1989. This group aimed at the realization of an optical computer and considered the light source of parallel processing. Among the small posts several $\mu$m in diameter, as shown in Fig. 9.1, a quantum well sandwiched between semiconductor DBRs is used as an active layer. In the experiment, current is supplied from above by the microprobe, and light is emitted from the top surface of the post. With this structure, room-temperature continuous operation was also achieved.

The above is a device that uses InGaAs/GaAs strain system \{1989 JEW\}. InGaAs can be grown on a GaAs substrate, and a DBR of GaAs/AlAs can be used to exhibit high performance as a surface emitting laser providing a 980-nm-wavelength band. However, this post-like shape is not thought to be practical.
DARPA

In order to counter the overwhelming strength of consumer technology in Japan, the U.S. converted their budget to prioritize new technology. Although it was the U.S. military budget, which was used for defense because of the East–West Cold War, there was a situation where it could be diverted to civilian use. In other words, the defense budget was converted, and a large budget was given to the Defense Advanced Research Projects Agency (DARPA).

One example was array technology, and optoelectronics also attracted attention. The surface emitting laser was paid a great deal of attention for both of the above reasons, as the conditions for the budget investment were the presence of innovation. In the era of the 41st President, George H. W. Bush, it was the first “innovation.”

Around that time, when I went to the United States, related professors were often visiting Washington, D.C., i.e., visiting DARPA, to apply for the project. Three projects, including the University of California at Santa Barbara (UCSB), the University of Illinois (Univ. Illinois), the University of New Mexico, and most major universities, were good, and eventually all three were accepted. In this way, research cooperation and competition intensified.
Chapter 10
Surface Emitting Lasers of Various Wavelengths: Development of Basic Technology

- From the near-infrared to red and then blue.
- Crystal growth is a key technology.
- Green is the most difficult.

10.1 Surface Emitting Lasers and Materials

Figure 10.1 shows the wavelength of the surface emitting laser and the semiconductor material used for it. At first, surface emitting lasers with a near-infrared wavelength in the 850-nm band were put into practical use, and a wide range of devices were made one after another. Let’s look back on the pattern of the research. In this chapter, technical terms, etc., will appear, but this is a technical review, after all. In addition, the elements appearing as various compounds and their names are summarized in the glossary at the end of the book.

10.2 Surface Emitting Laser with 780–850-nm Wavelengths

A GaAlAs/GaAs surface emitting laser, as shown in Fig. 10.2, has been commercialized from research and development as the most familiar laser covering a wavelength band of 780–850 nm. In the second half of the 1990s, technological advances such as reflector graded composition and doping, optimal design, etc., reached a level at which current thresholds smaller than a mA and practically sufficient output power of 10 mW were obtained. Furthermore, 57% conversion efficiency of power was reported for an
10.5 Problems with Surface Emitting Lasers in the 1-Micron-Wavelength Band

(1) Problems in surface emitting lasers in the 1-μm-wavelength band

First, so-called long-wavelength surface emitting lasers with a wavelength of 1300 nm or 1550 nm are expected to be applied to parallel light communication systems. However, research by the author has found that the following difficulties in the commonly used InGaAsP/InP semiconductors are strictly present, particularly in surface emitting lasers. It becomes a little more specialized, but the details are described by the reference document [2000 IGA]. The following is an overview.

(2) Long-wavelength surface emitting lasers: What are the problems?

a. Auger absorption and valence band absorption are large.
   • There is an inherent property of the material that instantaneously absorbs light in time even when it is emitted.
b. When used as a semiconductor Bragg reflector, the difference in refractive index between InGaAsP and InP is small.
   • It is necessary to increase the number of layers to 40 or more to increase the reflectance.
c. The barrier in the conduction band of InGaAsP and InP systems is small.
   • Electrons leak before emitting light.

(3) Formation of reflectors

If a surface emitting laser in this wavelength range is available, it is useful for optical fiber communication, so I had to clear it in any case. Therefore, we tried various device realization schemes. Especially in this system, it is important how to construct a reflector, and one of them is considered a compound reflector, and it was tried by a kind of molecular beam epitaxy (MBE) called the chemical beam epitaxy (CBE) method. For continuous operation, heat radiation from the reflector is also difficult in this system, and magnesium oxide (MgO)/silicon (Si) was used to enable the first room-temperature operation at a wavelength of 1300 nm. Higher-temperature operation was also realized using the Al₂O₃/Si reflector.

Other methods were tried in the United States and Europe. The bonding method by UCSB is a method of bonding a wafer including an active region of InGaAsP/InP and another wafer including a GaAs/AlAs reflector. Pulsed oscillation at 144°C, continuous operation at a threshold of 0.8 mA, and a temperature of 69°C and 71°C were reported in the 1500-nm-wavelength band.

In 1998, an output of 1.5 mW or more was obtained by a tandem-type laser in which a photo-pumped resonator with a wavelength of 1300 nm was
Chapter 12
The Internet and Smartphones: The Surface Emitting Lasers Within

• Computer and optical fiber communication.
• Capillary of the internet: LAN.
• Smartphone is another form of infrastructure.

12.1 Spread of the Internet
The internet is a new technology, shown in Fig. 12.1. Many internet facilities are based on computers and high-speed optical fiber communication lines, and our own computers play an important role. The main line is laid by a company, but this will use the existing utility poles, roads, railways, tunnels, etc., and the construction of the branch line is paid for by subscribers. There is no exchange facility in the internet, so a computer at an intermediate provider instructs where to send mail. Among the communication lines, surface emitting lasers are often used in LANs.

I did not think that the internet would lead to the practical application of surface emitting lasers. The common sense in fiber-optic communications in Japan was fixed on using single-mode fiber and long-wavelength single-mode semiconductor lasers. Even as an author, the intent behind the invention of the surface emitting laser was originally a single-mode laser, so it can be said that I was released from the curse of this stereotype or prejudice.

However, the United States was different. Chapter 6 mentioned the conflict between Bell Labs and IBM, but it is my point of view that the history has continued since then. In other words, a method using multi-mode fibers and VCSELs was introduced for optical interconnects in short-distance LANs and data centers.
Chapter 14
Surface Emitting Laser Patent: Too Early

- Have you applied for a patent?
- University disputes and patents.
- When is it too early?

14.1 The Surface Emitting Laser Patent

Sometimes I am asked the question, “What is the patent for surface emitting lasers?” The author also claims that some patents have been filed and patented, but they have been expired since 2000, when it was put into practical use.

Speaking of the 1970s, when I started researching, the so-called 1970 university disputes were over. It was a time when university people did not strongly think about industry–academia collaboration or commercialization. No, it was better to say that it was the opposite situation. National universities conduct research for the whole nation, and it was valued more than having one’s own ideas or providing for a specific company. The author was one of the researchers in such a situation, and it was a long time before the university was able to encourage patent applications. Even so, because it was engineering research, I applied for some patents. In my research career, I applied for about 50 patents, including the surface emitting laser. One such patent is shown below:

- Tokyo Tech Patent

Kenichi Iga, Yasuharu Suematsu, Katsumi Kishino, Haruhisa Soda
Application date: January 9, 1980
Published: August 08, 1981
Publication date: November 30, 1989
Patent No. 1-56547
Afterword

The surface emitting laser I invented is now brightening. About 43 years after the 1977 draft, I turned 77 years old in 2017. For me, “77” is a number to commemorate, e.g., attached to the plate of a private car. I made a T-shirt designed with the number (see Fig. AT.1).

Theodor Maiman demonstrated ruby laser oscillation in 1960. 60 years have passed since then, and the academic and optical industry fields related to optoelectronics have emerged. The shipments in Japan for the optical industry in 2015 totaled 17 trillion yen, and the domestic production amount was 8 trillion yen (according to the Optical Industry and Technology Development

Figure AT.1  77-T-shirt.