Advancing beyond

White Paper

High-Output Semiconductor Laser

Contents

1 Introduction

Following the successful development of room-temperature laser oscillation in 1970, the semiconductor laser (hereafter Laser Diode or LD) was adopted for use as the light source for optical communications and has since made great advancements. In the late 1980s, 1.55-µm optical amplifiers (hereafter Erbium-Doped Fiber Amplifier or EDFA) using optical fibers doped with the rare-earth element erbium(Er) were reported[*1] followed by reports[*2] of 1.48-µm semiconductor lasers using an pumping light source; due to the ease of use, these optical amplifiers have been widely adopted and today play a key role in the growth of high-speed broadband communications. Development of this 1.4-µm band LD technology played a major role in the introduction of the Fiber Raman Amplifier[*3] (hereafter FRA), which uses Raman dispersion in the transmission optical fiber, in commercial communications networks and has improved the quality of long-distance optical fiber communications. As a result of this continuous technology revolution, long-wavelength band, high-output LDs have become key devices as pumping light sources.

Starting in the early 1970s, our company (called Anritsu Electric Co., Ltd. at that time) began R&D into LDs for use in measuring instruments. This product group composed of optical pulse testers, reference light sources, etc., using these developed LDs helped with the commercial rollout of optical-fiber communications networks. Then, in the early 1990s, we successfully developed the 1480-nm semiconductor laser for use as a pumping light source for optical fiber amplifiers. The rollout of these amplifiers caused increasing demand for pumping light sources. To meet the demand for products with high output and low power consumption, we started manufacturing high-reliability and stable modules starting from crystal growth.

This White Paper explains the operation principles, characteristics, and applications of high-output LDs developed as pumping light sources for the various types of optical fiber amplifiers.

2 Principles of High-Output Semiconductor Laser

2.1 Structure of Module and LD Chip

Figure 2.1 shows the external view of a high-output LD. This is called a butterfly type due to the 14 leads protruding from both long sides of the case. The high-output LDs produced by our company are basically classified into two types: the Fabry-Pérot type (hereafter FP) and the FP-type with attached Fiber Bragg Grating (FBG). Figure 2.2 shows the internal structure of the FP-type. It is called the FP-type due to the structure of the resonator using both reflective facets of the LD chip. The laser light from the LD chip is focused by a lens and coupled to a connected optical fiber via an optical isolator which stabilizes the characteristics

Fig. 2.1 External View of High-Output LD

by preventing the laser output light returning to the module due to reflection and also by preventing external light from entering the module. Either a single-mode optical fiber or a polarization maintaining fiber can be selected. The monitor photodiode (PD) is for monitoring the optical output level. A thermoelectric cooler (TEC) is also built into the module to prevent

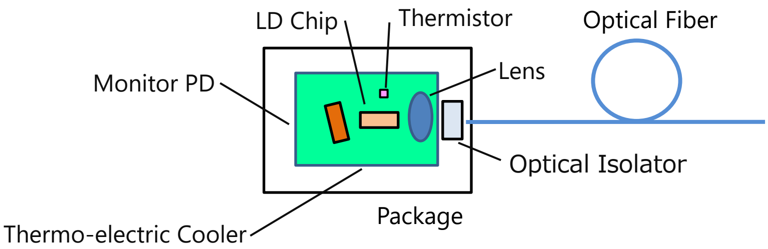


Fig. 2.2 Basic Structure of FP-type High-Output LD

temperature changes causing changes in the characteristics of the LD chip.

The LD chip itself uses a multi-quantum well (MQW) structure mainly fabricated using compounds of indium, gallium, arsenic, and phosphorus (hereafter abbreviated as InGaAsP). Semiconductor crystals can compose regular energy bands and these energy-band differences are called bandgaps. These bandgaps determine the lasing wavelength of the semiconductor light-emitting device including LDs. The quantum-well structure is formed by sandwiching the LD light-emitting region (active layer) between a several-nm-thick semiconductor with narrow bandgaps (well layer) and a semiconductor with wide bandgaps (barrier layer). As shown in Fig. 2.3, the MQW structure is a pile of quantum well layers. This several-nm-thick semiconductor generates an effect called the quantum effect which rapidly improves performance such as reducing the LD threshold current and increasing the light output. Our company has adopted an asymmetrical clad structure with the aim of further increasing the high output and lowering the power consumption. The clad is the layers above and below the active layer through which current passes. Our asymmetrical clad structure is composed of the n-clad side (lower side of active layer in Fig. 2.3) using the same InGaAsP as the active layer which reduces the light distribution at the p-clad side, making it thinner.[4-7] This unique structure cuts the optical absorption and electrical resistance of these layers to implement even higher output and lower power consumption.

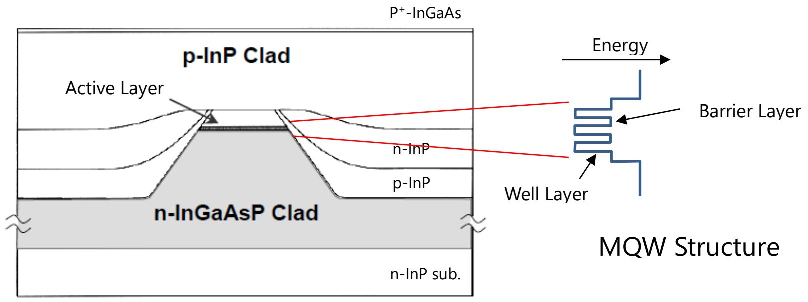


Fig. 2.3 Cross-Section of High-Output LD

Additionally, there is also a low-power-consumption version which is achieved by allowing the temperature T_{LD} of the LD chip to rise to 35°C from the previous temperature of 25°C. Increasing T_{LD} suppresses power consumption by the TEC and although the power consumption of the LD chip rises slightly, the total consumed power of the LD chip and the TEC is lower than products with the same optical output power.

2.2 FP-type Semiconductor Lasers with FBG

The center lasing wavelength of FP-type semiconductor lasers is distributed around a width of about 15 nm when looking at different modules and shifts in accordance with the LD current. Although this characteristic is not a problem for pumping light sources for EDFA, it is not a desirable characteristic for FRA. Consequently, some products are available with an attached FBG as a device to stabilize the lasing wavelength. The basic structure is shown in Fig. 2.4. The FBG is a fiber-type optical system that reflects light of specific wavelengths. Using

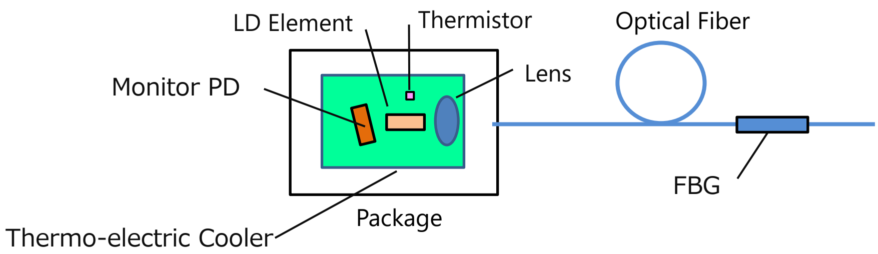


Fig. 2.4 Basic Structure of FP-type LD Module with FBG

this to return light of the required wavelength to the LD chip helps keep the lasing wavelength at an approximately constant value. As a result of this operation principle, an optical isolator like that used with an FP-type LD module shown in Fig. 2.2 does not included. The LD chip structure is the same as the FP-type, and the monitor PD and TEC are also mounted in the same way as the FP type.

2.3 Precautions

Since the high-output LD generates heat as a result of the high optical output and large current, the following points should be noted. For more details refer to "LD Operating Precautions" appended to the purchased product.

- The heatsink attached to the LD module should be in accordance with our mounting surface specifications and degree of flatness.
- When mounting the heatsink to the module, tighten the mounting screws to the required torque in the specified sequence.
- Ensure that bend radius of the fiber is larger than 30 mm.

Additionally, set the low-power-consumption version to the specified LD temperature (T_{LD} = 35°C). Since FP-type LDs with FBG do not have a built-in isolator, take care to suppress any back-reflection light or light leaking from the connected FRA as far as possible.

3 Characteristics of High-Output Semiconductor Lasers

3.1 Module Characteristics

Table 3.1 lists the main high-output semiconductor laser products. They are all butterfly type. Additionally, there are some separately available products with a maximum output power of less than 150 mW; they are compact, cylindrical modules because they do not have a built in TEC.

Table 3.1 Main High-Output Semiconductor Laser Products

Category	Optical Output [mW]	Center Wavelength [nm]	LD Temperature T_{LD} [°C]
1.31-µm FP-LD	100, 500	1310	25
1.48-µm FP-LD	120 to 500	1465 to 1480	25
	550 to 650		35
1.55-µm FP-LD	100, 450	1550	25
1.4-µm FP-LD with FBG	300 to 400	1420 to 1499	25
	410 to 500	1420 to 1485	25
1.4-µm FP-LD with FBG low-power-consumption version	300 to 500	1420 to 1485	35
1.3-µm FP-LD with FBG	500	1340, 1360	25

Table 3.2 lists the key specifications of the AF4B150CA75 model as an example of the characteristics of a 1.48-µm FP-type LD with a rated output power P_f of 500 mW and a center wavelength λ_C of 1475 nm. Figure 3.1 shows the current versus optical output characteristics and the lasing spectrum. Graph (a) in the same figure shows no kink in the curve (discontinuous change in LD current versus optical output power), indicating the excellent properties of this model.

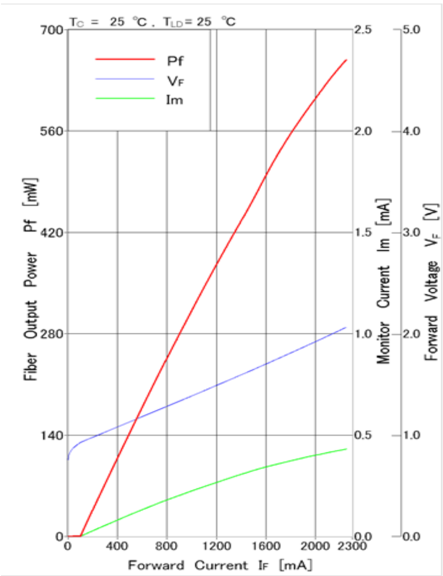
Table 3.2 Key Specifications of FP-type LD Model AF4B150FA75L

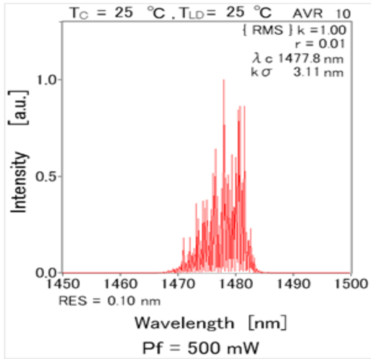
(T_{LD} = 25°C, Case Temperature T_C = 25°C)

Item	Symbol	Measurement Condition	Min.	Typ.	Max.	Units
LD Forward Voltage	V_F	P_f = 500 mW, BOL			2.2	V
Threshold	I_{th}	BOL			180	mA
LD Forward Current	I_F	P_f = 500 mW, BOL			1800	mA
Center Wavelength	λ_C	P_f = 500 mW, RMS (–20 dB)	1460	1475	1490	nm
Specral Half Width	Δλ	P_f = 500 mW, RMS (–20 dB)		5	10	nm
Monitor Current	I_d	P_f = 500 mW, V_{RD} = 5 V	100		2000	μA
TEC Voltage	V_C	I_F = EOL, T_C = 70°C			3.60	V
TEC Current	I_C	I_F = EOL, T_C = 70°C			3.10	A

BOL: Beginning of life; EOL: End of life, EOL I_F is 1.2 times BOL I_F

V_{RD}: Monitor PD reverse voltage; RMS: Root Mean Square (value using optical spectrum analyzer RMS method)





(a) Optical Output/Voltage/Monitor Current (b) Lasing Spectrum

Fig. 3.1 Example of FP-type LD Characteristics (AF4B150FA75L)

Next, Table 3.3 lists the key specifications of the AF4B250FU550FA model as an example of the characteristics of the low-power-consumption 1.48-μm FP-type LD with FBG with a maximum rated output power P_f of 500 mW and a center wavelength λ_C of 1455 nm. In comparison to the FP-type, the center wavelength accuracy is higher and the spectral half width is narrower, which are ideal characteristics for implementing this model as an FRA pumping light source. This low-power-consumption model has a total power consumption for the LD and TEC of less than 10 W. Figure 3.3 shows the current versus optical output characteristics and the oscillation spectrum. Like the FP-type, Fig. 3.2 shows no kink in the curve (discontinuous change in LD current versus optical output power), indicating the excellent properties of this model.

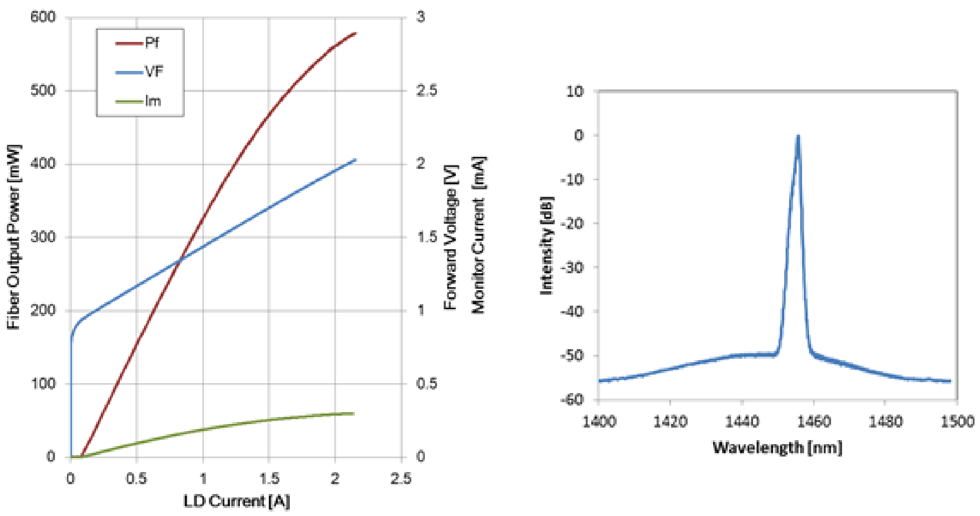
Table 3.3 Key Specifications of FP-type LD with FBG Model AF4B250FU550FA

(T_{LD} = 35°C, Case Temperature T_C = 25°C)

Item	Symbol	Measurement Condition	Min.	Typ.	Max.	Units
LD Forward Voltage	V_F	P_f = 500 mW, BOL			2.2	V
Threshold	I_{th}	BOL			180	mA
LD Forward Current	I_F	P_f = 500 mW, BOL			1750	mA
Center Wavelength	λ_C	P_f = 500 mW, RMS (–20 dB)	1454.0	1455.0	1456.0	nm
Specral Half Width	Δλ	P_f = 500 mW, –10 dB			3.5	nm
Monitor Current	I_d	P_f = 500 mW, V_{RD} = 5 V	100		2000	μA
TEC Voltage	V_C	I_F = EOL, T_C =75°C			2.75	V
TEC Current	I_C	I_F = EOL, T_C =75°C			2.25	A

BOL: Beginning of life; EOL: End of life, EOL I_F is 1.15 times BOL I_F

V_{RD}: Monitor PD reverse voltage; RMS: Root Mean Square (value using optical spectrum analyzer RMS method)



(a) Optical Output/Voltage/Monitor Current (b) lasing Spectrum

Fig. 3.2 Example of FP-type LD with FBG Characteristics (AF4B250FU550FA)

3.2 Reliability

Table 3.4 lists the reliability test results for the 1.48-μm high-output LD. The test conditions were in compliance with the Telcordia GR468-CORE standard for evaluating communications devices. All samples passed every test without failures. Figure 3.3 shows the results of the 2000-hour high-temperature operation test; the change in level during this period was ±0.15 dB and all samples operated stably. FIT (Failure In Time) is a failure-rate index indicating the average number of failures per 10^9 hours. The AF4B150Fxxxx series of general FP-type LD products (T_{LD} = 25°C) has a FIT count of 27 over 20 years while the low-power-consumption AF4B150FA75LA model (T_{LD} = 35°C) has a FIT count of 63 for the same period, confirming that Anritsu' high-output LDs have sufficient reliability as devices for communications applications.

Table 3.4 1.48-μm FP-type LD Reliability Test Results

Test Item	Referred Standard		Test Condition	Number of Samples	Number of Failure	Results
Mechanical Shock	Telcordia GR 468 CORE	MIL-STD-883, METHOD 2002	4,900 m/s^2, 1 ms, 6 axis, 5 times/axis	11	0	Good
Vibration		MIL-STD-883, METHOD 2007	196 m/s^2, 20 to 2000 Hz, 4 minutes/cycle 3 axis, 4 cycles/axis	11	0	Good
Thermal Shock		MIL-STD-883, METHOD 1011	ΔT = 100°C, 15 times	11	0	Good
Solderability		MIL-STD-883, METHOD 2003	245° ±5°C, 5 ±0.5 s	11	0	Good
Fiber Pull Test	Telcordia GR 468 CORE		9.8 N, 3 times, 5 s	11	0	Good
Fiber Integrity-Side Pull Test			4.9 N, 90 degrees, 22 to 28 cm from device housing	11	0	Good
High Temperature Operation			T_C =70°C, T_{LD} = 25°C ACC drive, 2000 h	11	0	Good
Temp. Cycling	Telcordia GR 468 CORE	MIL-STD-883, METHOD 1010	–40 to +85°C, 500 cycles	11	0	Good
High-Temperature Storage	Telcordia GR 468 CORE		85°C, 2000 h	11	0	Good
Low-Temperature Storage			–40°C, 72 h	11	0	Good
Damp Heat	Telcordia GR 468 CORE	MIL-STD-883, METHOD 1018	85°C/85%, 2000 h	11	0	Good
Internal Moisture		MIL-STD-883, METHOD 1018	Water vapor ≤5000 ppm	11	0	Good
ESD		MIL-STD-883, METHOD 3015	Threshold voltage ≥500 2000 V, R = 1.5 kΩ, C = 100 pF, 5 times	11	0	Good

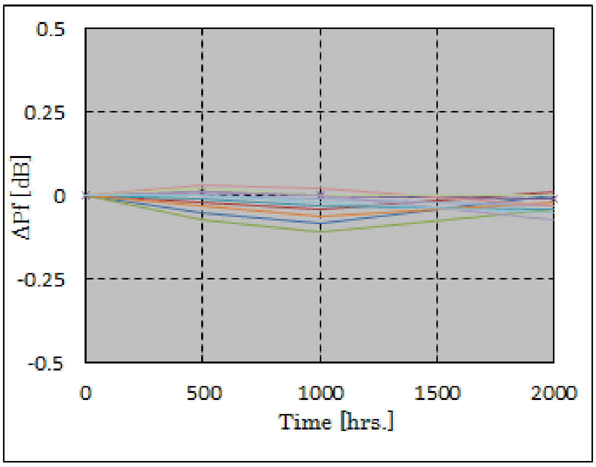


Fig. 3.3 High-Temperature Operation Test

4 Application Fields

4.1 Erbium-Doped Fiber Amplifiers (EDFA)

Figure 4.1 shows an example of an EDFA configuration using backward pumping. Either a 0.98-μm or 1.48-μm LD light source can be used as the pumping light; pumping at 1.48 μm has the following features compared to 0.98 μm.

・ Higher power conversion efficiency from pumping light to optical output power

・ Wider pumping light wavelength absorption width, eliminating the need for an FBG to control the pumping light wavelength

This feature is due to the built-in optical isolator which can be implemented to suppress reflected light. Conversely, pumping at 0.98 μm requires an FBG to stabilize the LD, therefore there is no built-in isolator. This wavelength requires a large isolator, which is difficult to build into a standard package.

・ For long-distance transmission where it is difficult to supply power to the relay point, 1.48μm LDs are used in a remote pumping configuration. In this case, since the loss and dispersion of the 0.98-μm pumping light are large, pumping requires use of a 1.48-μm light source.

Since EDFA gain is correlated with pumping light output power, a method is known for increasing the high output further by combining the polarizations of two high-output LDs as pumping light sources as shown in Fig. 4.1. We also have LD modules using polarization-maintaining fiber for this application.

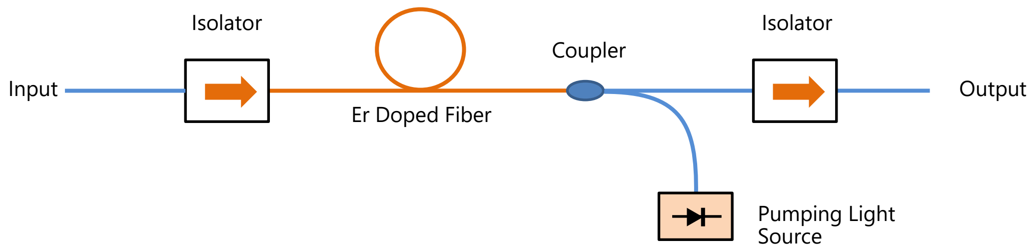


Fig. 4.1 Basic Configuration of EDFA

4.2 Fiber Raman Amplifiers (FRA)

An optical amplification effect is generated in standard single mode optical fiber (SMF) by injecting strong pumping light to create a non-linear phenomenon called Raman scattering. As shown in Fig. 4.2(a), when using a pumping light source with a wavelength of 1.45 μm, the center gain wavelength is about 100 nm to the longer-wavelength side. With a Raman amplification, the amplification wavelength region per pumping light wavelength wave is not

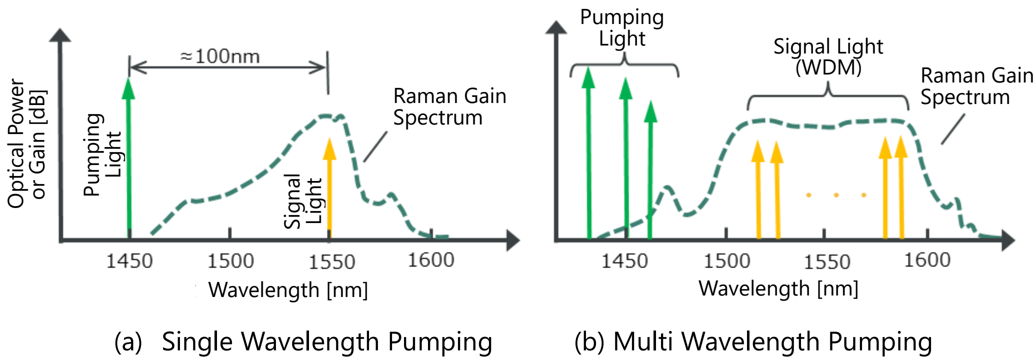


Fig. 4.2 Relationship between Fiber Raman Amplifier Pumping Light and Gain

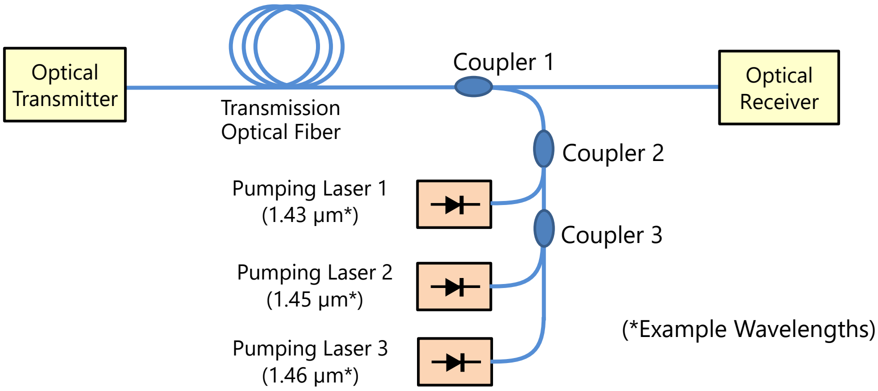


Fig. 4.3 Basic Configuration of Transmission using Fiber Raman

wide. Consequently, as shown in graph (b) of the same figure, when wanting to amplify optical signals with multiple wavelengths, widening the amplification band requires combining multiple pumping light wavelengths. The pumping light wavelength and power are adjusted so that the gain band in the fiber is flattened. Although the FRA amplification is lower than that of EDFA relative to fiber length, since general-purpose SMF can be used as the optical amplifier medium, it has been commercialized as a distributed optical amplifier by injecting pumping light into the transmission fiber. Figure 4.3 shows a transmission system using a fiber Raman amplifier configuration. Since the Raman gain depends on the pumping light polarization, either a depolarizer (polarization scrambling device) is installed at the output of the pumping LD or the polarization light of the pumping light source is canceled by combining the polarizations of two LDs. (This configuration is omitted in Fig. 4.3.)

The transmission method combining EDFA and a distributed Raman amplifier has a better optical SN ratio compared to the stand-alone EDFA and is expected to reduce signal degradation due to unwanted non-linear optical phenomena in the optical transmission path, and there are reports of being able to extend transmission distances as a result.[8] On the other hand, a high-output pumping light source is required because the pumping efficiency of the Raman amplifier is not high, and as shown in Fig. 4.3, the cost is much higher than EDFA due to the need to use multiple pumping light sources to increase the gain wavelength band and remove polarizations.

A higher-order pumping Raman amplifier method in which the Raman pumping light source itself is Raman-amplified has been suggested. Figure 4.4 shows the relationship between each pumping light wavelength, Raman gain spectrum and optical signal wavelength. The pumping light source for Raman amplification of the optical signal is called the primary pumping light and the pumping light source for Raman amplifying this primary pumping light source is called the secondary pumping light. Figure 4.5 shows the configuration for this method. Using this higher-order pumping Raman method is reported to improve the effective NF by 1 to 2 dB compared to amplification using only the primary pumping light[9].

Our company also produces 1.3-μm FP-type LDs with attached FBG for this application.

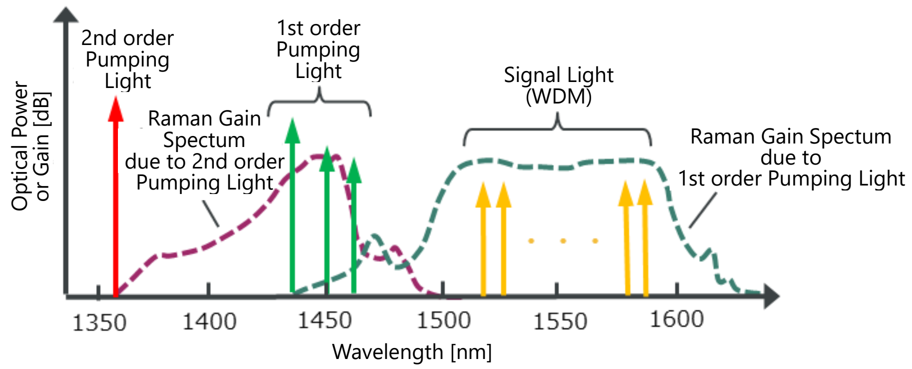


Fig. 4.4 Relationship between Higher-Order Pumping Fiber Raman Amplifier and Gain

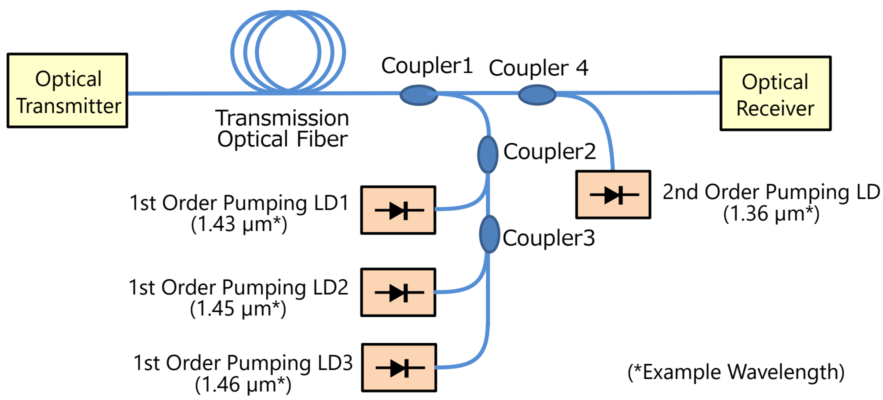


Fig. 4.5 Basic Configuration of Higher-Order Pumping Fiber Raman Amplifier

4.3 Fiber Lasers and ASE Light Sources

Our company also manufactures 1.3 to 1.55-μm band high-output lasers for use as pumping light sources for fiber lasers and fiber ASE light sources. Fiber lasers are broadly classified into

CW lasers and pulse lasers. Furthermore, pulse lasers are divided into passively mode-locked types suitable for sub-picosecond pulse generation, actively mode-locked type suitable for picosecond pulse generation at a precise period, and Q-switch types suitable for generating large pulses. Figure 4.6(a) shows the configuration of a ring-resonator type CW laser. This laser design oscillates by selecting the wavelength of the optical output from the EDFA using a bandpass filter and feedback. Graph (b) in the same figure shows an example of the configuration of a passively mode-locked type pulse laser, which uses a saturable absorber. This device has a variable absorption rate (transmittance) depending on the power of the injected light; the pulse width can be shortened by using a material with a fast responsivity. Use of carbon nanotubes and graphite has been suggested for the materials of the saturable absorber[10). Moreover, since the sub-picosecond pulse has a wide optical spectrum width, sometimes the optical filter shown in Fig. 4.6(b) is omitted.

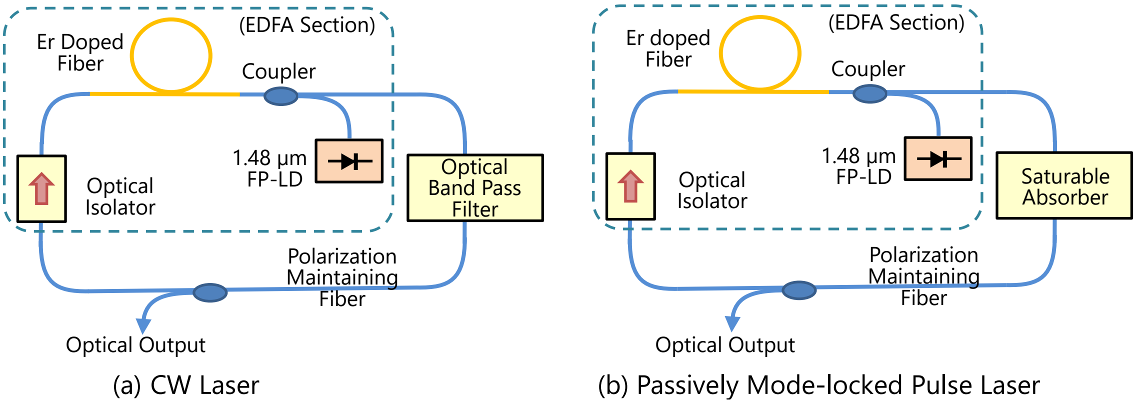


Fig. 4.6 Example of Fiber-Type Laser

Sub-picosecond pulse lasers are used for research into high-speed physical phenomena; picosecond to nanosecond pulse lasers have applications in optical sensing, such as laser range finding and Light Detection and Ranging (LiDAR). High-output pulse lasers and CW lasers are used for laser machining, cutting, etc.

On the other hand, fiber ASE light sources use only the gain produced by the amplified spontaneous emission (ASE) from an EDFA with no input. This light is unpolarized and has a bandwidth of several tens of nm. Since the optical output power is higher than other white light sources, it is ideal for measuring the loss characteristics of 1.55-μm band optical parts.

4.4 Optical Sensing and Other Applications

Generally, since 1.3 to 1.55-μm band semiconductor lasers have a long life, they are commonly used in optical sensing and other fields. In particular, light near 1.55 μm has a low risk of causing damage to the retina of the eye (Eye Safe) so it is often used for free-space optical sensing such as LiDAR. Additionally, wavelengths in this region suffer minimum optical loss when propagating through optical fiber so they are often used as light sources for long-range fiber sensing. Some other commercial applications are described below.

a) Semiconductor Product Analysis

The Infrared Optical Beam Induced Resistance Change (OBIRCH) method has been reported as a technology for fault analysis of silicon integrated circuits[11]. Using this method, a bias voltage is impressed on the DUT while it is scanned with a 1.3-μm laser (Fig. 4.7) to detect heat generated by changes in wiring resistance and leakage current as well as voids (defects).

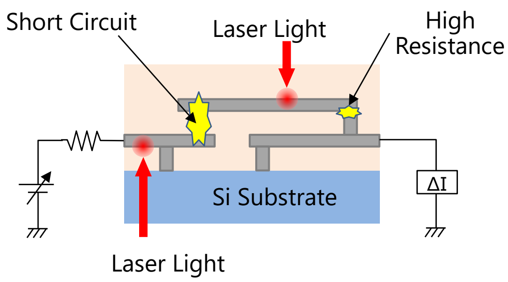


Fig. 4.7 IR-OBIRCH Principle

b) Medical Fields

Lasers are being actively promoted in medical fields[12]. For R&D into *in vitro* fertilization, lasers are being used to operate on the *zona pellucida* protecting ova and fertilized eggs[13-15] because the small size and easy handling of semiconductor lasers is ideal for use under the microscope. In particular, 1.48-μm band light does not easily damage cellular DNA and semiconductor lasers at this wavelength are being commercialized in various medical systems[15].

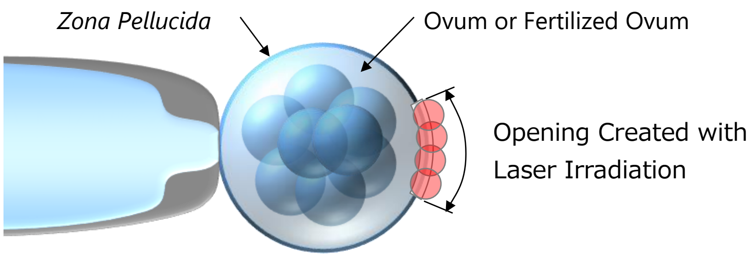


Fig 4.8 Diagram of Cell Laser Irradiation

However, please note that the specifications for our laser products are not optimized for these optical-sensing applications. For example, the pulse current driving characteristics are not guaranteed.

5 Conclusions

Development of optical fiber communications and 1.3 to 1.55-μm band semiconductor lasers has made great progress. In particular, the appearance of optical fiber amplifier technology has promoted development of high-output lasers, which in turn has resulted in ultra-broadband optical communications networks. Additionally, the high-output lasers resulting from this process are now finding applications in new fields, such as optical sensing and medicine.

Anritsu's high-output semiconductor pumping lasers are playing key roles in modern optical communications and assuring people's safety and health.

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