Overview of Research on Distributed Feedback Laser Diode in the wavelength of 1.55 μm

1. Study of distributed feedback semiconductor lasers in the long wavelength region

Conventionally, Fabry-Perot (FP) lasers, which shows multi-longitudinal mode oscillations, have been used as light sources for optical communications systems. For including light with different wavelength in a pulse signal, the pulse width is broadened during transmission due to the wavelength dispersion of the propagation. In the system of the pulse interval shortened or the transmission with long haul, the successive pulses become overlapped during the transmission. This phenomenon limits the high bit-rate and long-haul transmission.

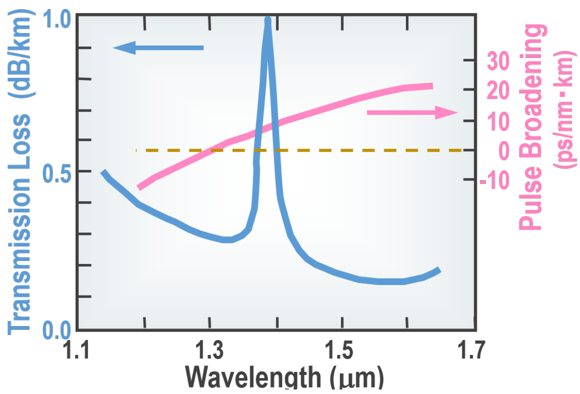


Fig. 1. Transmission loss of optical fiber and wavelength dispersion of optical pulse broadening

Instead of this FP laser, the distributed feedback laser as one showing single-longitudinal- mode oscillation was studied. This laser has corrugation with the period of 240 nm as an optical filter under the emitting layer.

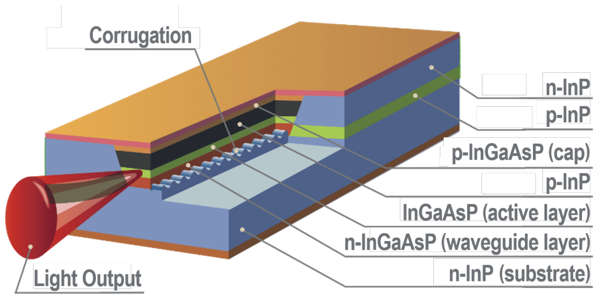


Fig. 2 Structure of DFB Laser Diode

A DFB laser was studied by using GaAs and related materials in 1970s. It could not be used because of its short device lifetime. Its characteristics were not sufficiently analyzed. In these situation, both techniques of the epitaxial growth and the fabrication process were established. In 1981 the first continuous-wave (CW) oscillation at room temperature was successively realized.

Before Matsuoka's work

~GaAs~

1971 Principle confirmation of Distributed Bragg Reflector (DBR) laser — H. Kogelnik *et al.* (AT&T BELL)

1972 Theory of DFB laser — H. Kogelnik *et al.* (AT&T BELL)

1973 Couple mode theory — A. Yariv (CALTECH)

1974 Research on the theory of the effect in the corrugation phase at the end facet — W. Streifer (XEROX)

1975 Room-temperature CW oscillation of GaAs/GaAlAs DFB laser diode — M. Nakamura *et al.*(Hitachi, Caltech)

~InP~

1980 Pulsed Operation of InGaAsP/InP DFB laser diode — O. Mikami (NTT)

Matsuoka's works

1981 First CW operation at room temp.

1983 Development of etchant suitable for nm-order microfabrication

Suppression of thermal deformation of corrugation during epitaxial growth

1984 Experimental confirmation on effect of corrugation phase at the facet and proposal of LD structure for SLM oscillation

1985 Prediction of temperature range in SLM oscillation

Design of LD structure for high-efficiency, low threshold current and high yield in fabrication yield

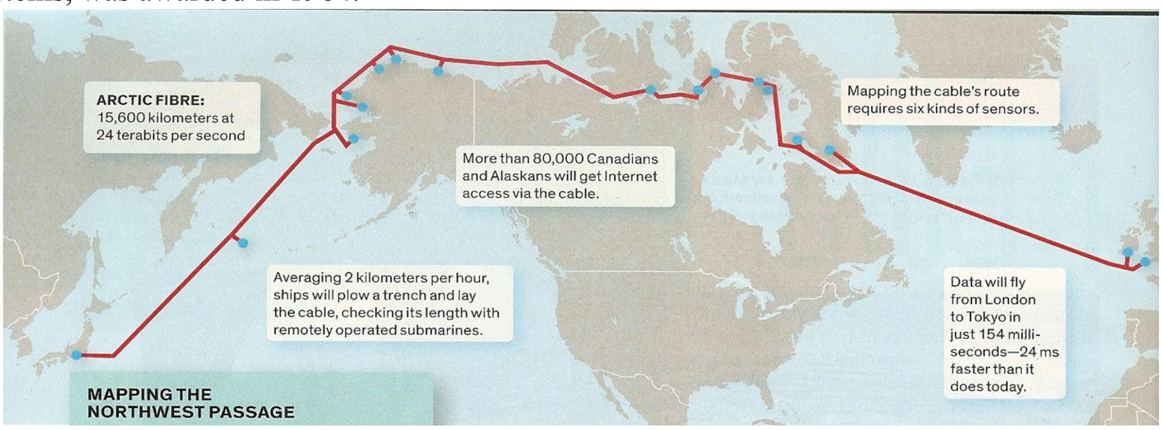
1986 Light output power of 45 mW under CW operation at room temp.

Fig. 3 Development history of DFB Laser Diode

Later, the device characteristics were precisely analyzed. Based on these analyses, the structure with high yield of SLM oscillation was designed. This DFB LDs were supplied to the researchers in the field of the optical communications systems, and as a result DFB LDs were useful for the optical communications systems since 1982. From 1983 to 1985, the fabrication technique of DFB LDs was transferred to a few deice makers.

Presently, DFB LDs have been widely used as light sources for high-bit-rate and long-haul optical communications systems in Japan, Europe, and USA. In Japan, ese system, the system over ten thousands km has been constructed. Its bit-rate is 100Gb/s per wavelength. Based on the characteristic of SLM oscillation, the concept of the wavelength division multiplexing (WDM) system has been created, and the 100-wavelength multiplexed system has been realized. Its bit rate reaches to 10Tb/s per fiber. This value corresponds to 1.56 G lines of conventional phones. It is not too much to say that DFB LDs have supported the advanced information society.

ECOC prize as the best paper award of European Conference on Optical Communications (ECOC), which was one of three biggest conferences on communications systems, was awarded in 1984.



Distance: 15,600 km, laying velocity of cables: 2km/h, laying fee: $850M, bit-rate: 24Tb/s, transmission time from Tokyo to London: 154 ms

Fig. 4 Optical fiber submarine cable through North Pole:

The research issues studied are concretely shown below.

Table 1. Key technologies for fabricating DFB LD

Technique	Issue	Technology before my work
Fabrication of Corrugation	Design and Construction of Dual-Beam Interferometer Pattern width: 0.12 μm	Minimum pattern width: 2 μm
	Photolithography photoresist thickness 30 nm	Minimum photoresist thickness: 0.5 μm
	Etchant for InP: Development of stable etchant with no generation of bubbles	Hydrochloric acid: unstable and generating bubbles
Epitaxial Growth	Cleaning of Corrugation Surface	Liquid Phase Epitaxy
	Keeping Corrugation Shape during Epitaxial Growth	No experience
Device Design	Design of Corrugation Shape	Couple-mode theory
	Probability of Single-Longitudinal-Mode Oscillation	No discussion

Starting the research on October, 1980

(a) Development of exposure system consisted of two-beam interferometer system

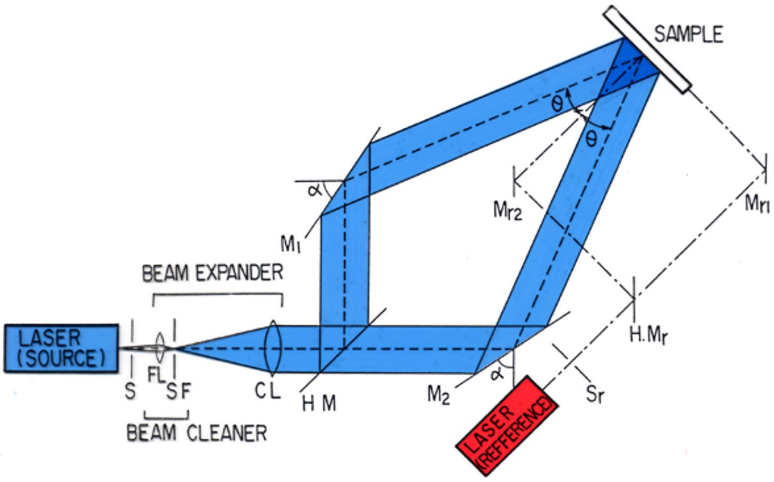


Fig. 5 Principle of exposure system consisted of two-beam interferometer system

Fig. 6 Externally sailed equipment of exposure system consisted of two-beam interferometer system

(b) Development of etchant with high controllability and reproducibility for processing InP

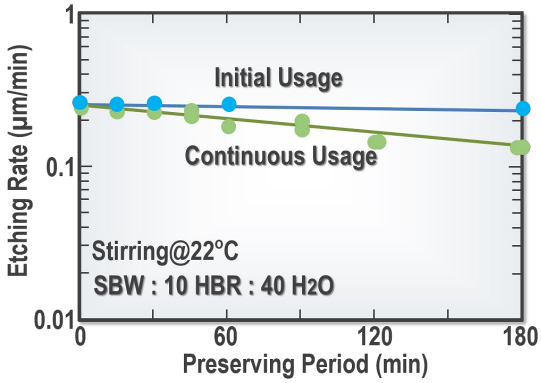
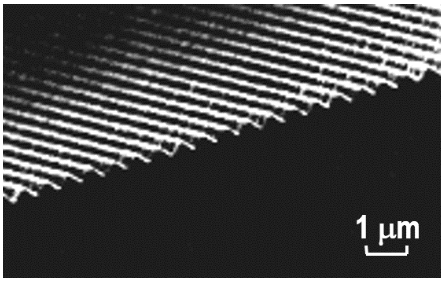


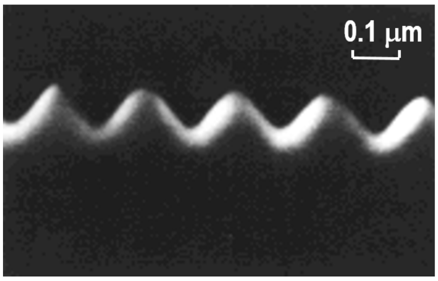
Fig. 7 Stability of Developed etchant for (001) InP substrate

SBW*: 10 HBr : 40 H_2O *SBW; Saturated Bromine Water

T. Matsuoka and H. Nagai, *J. Electrochem. Soc.* **133**, 2485 (1986).



(a) Bird view



(b) Crosse-sectional view

Fig. 8 SEM Photographs of corrugation with period of 197 nm formed on (001) InP substrate

(c) Development of the technique suppressing the thermal deformation of InP corrugation

When the device structure is grown pn the InP corrugation, the corrugation was thermally deformed in the reactor of a liquid phase epitaxy (LPE) system during the soaking duration in the reactor. This phenomenon was analyzed based on the thermal dynamics. Finally, to introduce a phosphine gas into the growth ambient, the device structure as successively grown without deformation.

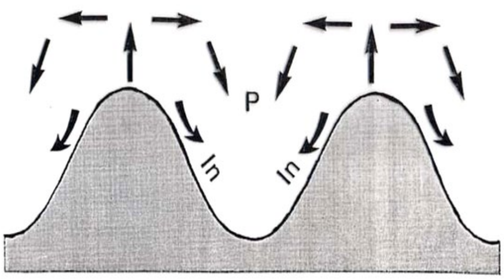


Fig. 9 Principle of mass transport

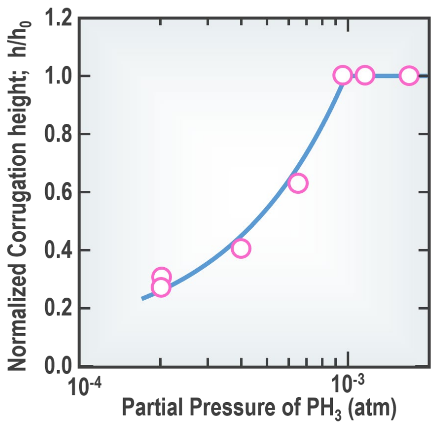


Fig. 10 Effect of introducing PH_3 into LPE reactor

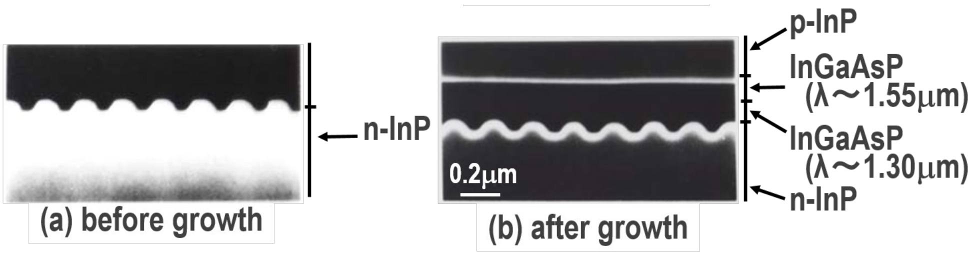


Fig. 11 Cross-sectional view of DFB-LD structure grown on corrugation

H. Nagai, Y. Noguchi, and T. Matsuoka, *J. Crystal Growth* **71**, 225 (1985).

(d) Effect of corrugation phase at the cavity facets

While changing the corrugation phase at the cavity facet by directly etching the cavity facet was changed, the device characteristics were measured. The characteristic of SLM oscillation was pointed out to depend on the corrugation phase at the facet.

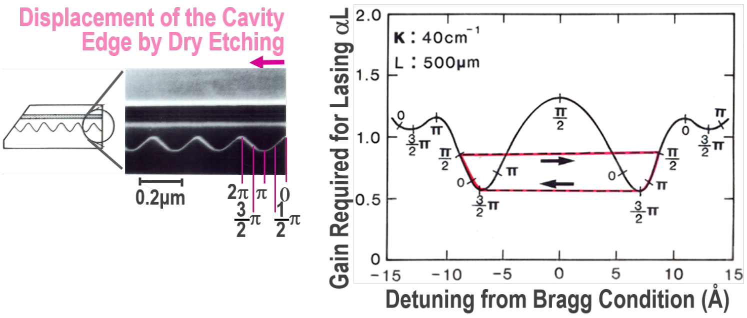


Fig. 12 Effect of corrugation phase at the cavity facet

T. Matsuoka, H. Nagai, and Y. Yoshikuni, *IEEE J. Quantum Electron.*, **QE-21**, 1880 (1985)

(e) Device design

The device structure of DFB LDs with high yield fabrication, high output power, and stable operation was designed through the analysis based on the couple mode theory considering the corrugation phase at the cavity facet.

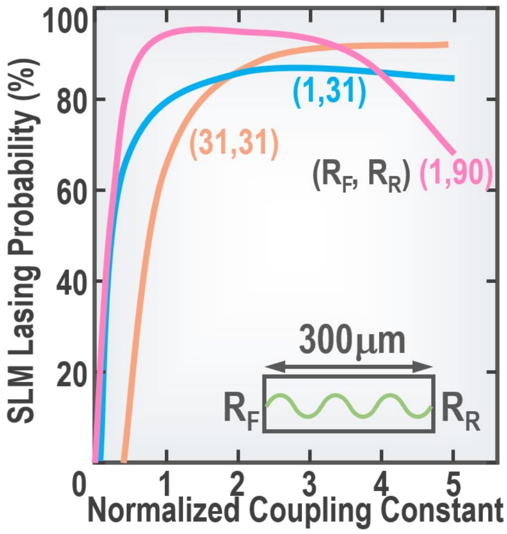


Fig. 13 Device structure of DFB LD and probability of SLM oscillation