RECENT DEVELOPMENT ON FIBER OPTIC DEVICES

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ABSTRACT

The advent of the fundamental transverse mode laser diodes and low loss optical fibers has extended the wavelength range for communication systems into the optical spectrum region. The indispensable elements for the optical communication systems are oscillator, transmission medium, and detector. Recent development in this area,with particular emphasis on the fundamental transverse mode laser diode and low loss quartz optical fiber, is reviewed.

Introduction

In 1970, Hayashi et al.,[1] Bell Laboratories, realized a double heterostructure laser diode which operates continuously at room temperature. In the same year, Kapron et al.,[2] Corning Glass Works, made a 20 dB/km loss quartz fiber by CVD method. These two epochmaking technology stimulated the research and development work on the "dream" communication, and now fiber optic communication is being realized in various application fields.

Microwave technologies greatly contributed to the rapid development of the fiber-optic technology.

Most of the systems are developed with 0.85 μm devices and multi-mode fibers so far. Research and development on longer wavelength devices (1.3 - 1.6 μm) and single mode fibers are progressing for realizing best transmission characteristics.

Fig. 1 shows progress in reduction of optical fiber loss and in lengthening life time of 0.85 μm lasers.

Laser Diode

Laser diodes and LEDs by two kinds of materials have been developed for fiber-optic sources. The short wavelength AlGaAs sources emitting the 0.85 μm spectral band which are controlled in lasing mode and enhanced in lifetime, are now widely being used. With the growing interest in the 1.3 to 1.6 μm spectral bands, where the fiber loss and dispersion are low, much efforts are made to develop InGaAsP sources for longer distance and higher bit-rate applications.

Mode and Structure. The fundamental transverse mode lasing has been realized both with short wavelength AlGaAs (0.8 - 0.9 μm) and long wavelength InGaAsP (1.2 - 1.6 μm) stripe-geometry-laser diodes, which is essential property required for fiber-optic sources. The transverse mode stabilized lasers exhibit the improved characteristics such as linear light output, low operation current, high efficiency, high frequency modulation, and low noise.

Concerning longitudinal mode, there are two type lasers by the waveguiding mechanism, the index-guide type and the gain-guide type. The former shows the single longitudinal mode under dc operation as first demonstrated in AlGaAs TJS (Transverse Junction Stripe) lasers,[3] while the latter shows the multi-longitudinal modes as confirmed by narrow stripe lasers such as the V-groove laser.[4] Figure 2 shows typical laser structures developed for fiber-optic sources.

Wavelength and Output. In AlGaAs lasers, the lasing wavelength extends from 0.9 μm of GaAs to 0.75 μm of $Al_{0.23}Ga_{0.77}As$ without increase of threshold current. TJS lasers has low threshold current of 15 - 30 mA in the wavelength range. The light output is limited by the catastrophic optical damage (COD) at the mirror surface due to intense light output density. COD occurs at a few MW/cm^2 of the light output which corresponds to 20 - 50 mW for the ordinary fundamental mode lasers. Recently, a notable improvement of COD has been realized in the "crank" type TJS lasers which has a COD level over 100 mW (10 MW/cm^2).

In long wavelength InGaAsP lasers, the lasing wavelength extends 1.2 to 1.6 μm with low threshold current density.[5] Particular interests are stressed on 1.3 μm lasers for wideband transmission by zero material dispersion of the fiber, and 1.6 μm lasers for long distance transmission by the lowest loss of the fiber. The fundamental transverse mode lasers are BH (Buried Hetero structure)[6,7] and BC (Buried Crescent) lasers[8] with very low threshold current of 10 - 20 mA. COD in the lasers exceed 10 MW/cm^2 which is attributed to the material property of very low surface recombination.

The practical level of the light output is usually set to be several mW at present because of the long term operation requirement in fiber-optic applications.

Modulation. The fundamental transverse mode laser has a wideband frequency modulation characteristics with reduced resonance-like peak. Figure 3 shows a typical frequency modulation characteristics of a TJS laser and a modulation bandwidth over 4 GHz has been obtained at a bias current 1.5 times threshold. Analogue modulation of lasers at 100 MHz shows very low distortion level of the 2nd harmonics less than 50 dB, which seems to enable them to be used in applications such as multi-channel CATV.

Recently, 8 Gb/s PCM direct modulation has been achieved in a TJS laser by R. Tell and S. T. Eng.[9]

Noise and Stability. Excess light intensity fluctuations of lasers are closely correlated with lasing mode instabilities. Light intensity fluctuations due to irregularities such as kinks and nonlinearities in their light-current characteristics by transverse mode instabilities are eliminated in the transverse mode stabilized lasers.

Longitudinal mode competition at certain bias conditions in index-guide lasers may yield a significant detrioration of S/N ratio. The noise can be stabilized in gain-guide lasers with multi-mode oscillation by the mode partition effect for oscillating modes although the background noise level is much higher than that of index-guide lasers.

Modal noise is caused by the effect of spatial filtering on speckle patterns in fibers, when coherent laser light is launched in a multi-mode fiber. Multi-longitudinal mode lasers are suitable for this end. To reduce the noise by index-guide lasers, multi-longitudinal oscillation by superposition of much higher frequency modulation current than that of signal is useful.

Lifetime. The lifetime of AlGaAs lasers has been drastically improved by introducing defect-free crystal growth technique, dielectric film coating to avoide surface detrioration due to oxidation, and Si submount between the laser chip and the heatsink using hard solder such as Au-Si instead of In. An MTTF over 10^6 hr has been estimated at room temperature in single-mode TJS lasers by high temperature accelerating test.[10]

Preliminary life test indicates that InGaAsP laser is stable and lifetime over 10^5 hr at 50 °C has been estimated in lasers such as BC lasers.

Module and Coupling. Various kinds of laser module with a fiber pigtail or a receptacle of a fiber connector are developed for practical use, in which efficient coupling techniques are needed for source to fiber. The techniques include micro-lenses and the use

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of tapered or bulb-ended fiber pigtails as shown in Fig. 4. Coupling losses are 1 - 2 dB for a standard multi-mode fiber, while are 5 - 7 dB by direct butt coupling. Recently, coupling losses as low as 3.5 dB has been obtained for 1.3 um lasers to single mode fiber by the use of a micro spherical lens and a graded rod index lens in confocal arrangement.[11]

Light Emitting Diode

In fiber optic communications, LEDs are used for short distance, lower bit-rate systems with the simpler drive circuitry, wider temperature range of operation and much higher reliability.

LEDs for fiber optic sources are designed to have high radiance with smaller light emitting area than that of the core of fiber to get efficient coupling to fiber. Typical structures of LED are shown in Fig. 5. For efficient coupling, a micro sphere lens is attached to the light emitting surface,[12] or a monolithic hemispherical structure is used.[13]

The modulation bandwidth of LED is typically 50 MHz for efficient light emission. Higher modulation bandwidth can be obtained by higher impurity doping in the active region at expense of light emitting efficiency. 1.3 μm InGaAsP LED is useful for non dispersion optical fiber. Lifetime of LED is estimated over 10^8 hr from accelerating test in AlGaAs and InGaAsP.

Table 1 shows the characteristics of the state-of-the-art lasers and LEDs for fiber-optic sources.

Detector

In short wavelength fiber-optic systems, Si pin photodiode and APD are well developed. Low noise and high speed APD has been realized in p^+pn planar mesa structure with eliminating carrier diffusion tail.

In long wavelength systems, Ge APD is used for high bit-rate applications. The performances of the device are improved in an n^+np structure by design optimization of multiplication noise, and a considerable low excess noise factor F(M) of 7 dB has been obtained at 1.3 μm for the multiplication factor M = 10.[14]

Recently, a low dark-current, high gain InGaAs/InP APD is developed for the use in the 1.0 - 1.6 um spectral region.[15] The p-n junction is in the InP, so that the high-field region is in the InP while the photogeneration region is in the InGaAsP.[16]

Another receiver design, using low dark current InGaAs pin photodiode and low noise GaAs FET preamplifier, offers an attractive alternative to the APD receiver at the long wavelengths.[17]

Table 2 shows the operating characteristics of detectors for fiber-optic systems.

Optical Fibers

Transmission characteristics of optical fiber is expressed by the transmission loss and the bandwidth. The loss curve in relation to the wavelength is V-shaped. In the shorter wavelength side the loss is determined by the Rayleigh scattering originated from the fluctuation of refractive index, and in the longer wavelength side by the tail of infrared absorption of Si-O bond. In the center low loss region, there are absorption peaks of O-H ions at 0.95, 1.24, and 1.38 μm, and the main subject to realize a low loss fiber was to eliminate the O-H ions. The bandwidth is mainly limited by the multi-mode dispersion in step- and graded-index multimode fibers, and by the material and structural dispersion in single mode fiber. The bandwidth can be expected to be a few tens of MHz in step-index type, a few hundreds of MHz to a few GHz in graded-index type by optimizing the refractive index profile, and a few to a 100 GHz in single mode type.

MCVD Method. The well known method for making preform of quartz fiber is the MCVD method which was developed in Bell Laboratories in 1974. In the method, unexpected impurities can be reduced and the fine control of refractive index is possible. However, the index dip often appears at the center of the fiber and the production speed is relatively low.

VAD Method. A new VAD method has been developed in NTT in 1977 to show better performance and possible capability of mass production.[18]

The method is a successive production method of mother rod. As shown in Fig. 6, fine glass soots synthesized from material gases in an oxy-hydrogen flame are deposited onto the end surface of the seed rod. A porous preform is then grown along the axial direction, which is gradually pulled-up to be consolidated into a transparent preform.

The first problem to be solved was to eliminate tinny bubbles completely. By using helium gas as consolidation environment, the problem was easily solved.

The second was the elimination of O-H ions. The O-H ions in the porous preform made by the hydrolysis reaction contains about 200 ppm of O-H ions. This value was reduced to be about 30 ppm after the consolidation process in dried He gas. O-H ions were further reduced to 0.03 ppm by making dehydration treatment at 1300°C flowing chemical reagents, chlorine or thionyl chloride, until the porous preform was entirely sintered. Furthermore, by optimizing the furnace and treatment procedure, and simultaneous synthesis of porous preform for cladding layer, O-H ion concentration is reduced to 0.001 ppm. With these improvements, loss below 0.5 dB/km was realized in a wide wavelength range between 1.2 - 1.7 um,[19] which is better than that of MCVD method.

The third problem was to control the refractive index profile. It is found that the concentration of GeO_2, which increases the index, depends on the surface temperature of the porous preform. It was controlled by the ratio H_2/O_2 in the oxy-hydrogen flame. Fibers made by the method has no index dip and has a superior transmission characteristics. The maximum bandwidth of 6.7 GHz·km and average of 0.5 to 1 GHz·km have been obtained, which are better than the values obtained by the MCVD method.

The fourth problem was to make a single mode fiber. Since a considerable part of optical field spreads into cladding layer in single mode fiber, it is necessary to purify the cladding layer as well as the core to reduce the loss. Multi-layered cladding is successively synthesized on thin core preform. When the diameter ratio of cladding and core is 5 to 7, loss below 0.5 dB/km is obtained between 1.2 to 1.75 μm.[20] Since the fiber has no center dip, bending loss is small.

A 100 km long fiber has been spun with a high drawing speed of 120 m/min from a large preform made by VAD method.[21] Comparison of the two methods is shown in Table 3.

Splicing. Two methods are known to splice fibers: butt joint method using adhesive of similar refractive index to the core, and fusion method. Arc prefusion method[22] is to butt fiber ends preheated with an electric arc. The method has advantages of smoothing scratches at the facets, no bubble introduction, and self axial adjustment effect due to surface tension. Average loss below 0.1 dB is obtained for both multi- and single mode fibers. The method enables short time splicing and is also applicable to multi-fiber cables.

Concluding Remarks

The properties of the optical fiber is much superior to that of the microwave transmission line. A subject of the fiber is to realize zero dispersion at the minimum loss wavelength of 1.6 μm. Improvement of mechanical strength and reducing production cost are also important for the fiber.

On the other hand, the laser diode is inferior to the microwave oscillator in coherency and stability at present. "Pure" single mode lasers for single mode fiber systems and "stable" multi-mode lasers for multi-mode fiber systems are favorable targets. Improvement of threshold current temperature dependence of long wavelength lasers is a subject to be achieved.

Micro-optics components such as connectors, isolators, switches, branching and coupling devices are now being developed for prospective high-grade fiber-optic systems.

References

1 Hayashi, I., Panish, M. B., Foy, P. W., and Sumski, S., "Junction lasers which operate continuously at room temperature," Appl. Phys. Lett., vol. 17, pp. 109 - 111, Aug. 1970.

2 Kapron, E. P. et al., "Radiation losses in glass optical waveguides," Appl. Phys. Lett., vol. 17, pp. 423 - 425, Nov., 1970.

3 Namizaki, H., "Transverse-junction-stripe lasers with a GaAs p-n homojunction," IEEE J. Quantum Electron., vol. QE-11, pp. 427 -431, July 1975.

4 Marschall, P., Schlosser, E., and Wolk, C., "A new type of diffused stripe geometry injection laser," Electron. Lett., vol. 15, pp. 38 - 39, 1979.

5 Arai, S., Suematsu, Y., and Itaya, Y., "1.11 - 1.67 um (100) GaInAsP/InP injection lasers prepared by liquid phase epitaxy," IEEE J. Quantum Electron., vol. QE-16, pp. 197 -205, Feb. 1980.

6 Hirao, M. et al., "Fabrication and characteristics of a narrow stripe InGaAsP/InP buried heterostructure laser," J. Appl. Phys., vol. 51, pp. 4539 - 4540, Aug. 1980.

7 Nagai, H., et al., "InP/GaInAsP buried heterostructure lasers of 1.5 um region," Japan. J. Appl. Phys. (Lett.), vol. 19, pp. L218 - L220, Apr. 1980.

8 Oomura, E., Higuchi, H., Hirano, R., Namizaki, H., Murotani, T., and Susaki, W., "Transverse mode control in InGaAsP/InP buried crescent diode lasers," Electron. Lett., vol. 17, pp. 83 - 84, Jan. 1981.

9 Tell, R., and Eng, S. T., "8 Gbit/s optical transmission with TJS GaAlAs laser and p-i-n detection," Electron. Lett., vol. 16, pp. 497 - 498, June 1980.

10 Nita, S., Namizaki, H., Takamiya, S., and Susaki, W., "Single-mode junction-up TJS lasers with estimated lifetime of 10^6 hours," IEEE J. Quantum Electron., vol. QE-15, pp. 1208 - 1209, Nov. 1979.

11 Saruwatari, M., and Sugie, T., "Efficient laser-diode-single-mode-fibre coupling using two confocal lenses," Electron. Lett., vol. 16, pp. 955 - 956, Dec. 1980.

12 Horiuch, S., Tanaka, T., Ikeda, K., and Susaki, W., "A new LED structure with a self-aligned sphere lens for efficient coupling to optical fibers," IEEE Trans. Electron Devices, vol. ED-24, pp. 986 - 990, July 1977.

13 Wada, O., et al., "A new type InGaAsP/InP DH LED for fiber optical communication system at 1.2 - 1.3 um," 1979 Optical Commun. Conf. (Amsterdam), paper 4.6-1.

14 Mikawa, T., et al., "A low-noise n^+np germanium avalanche photodiode," IEEE J. Quantum Electron., vol. QE-17, pp. 210 - 216, Feb. 1981.

15 Daidiuk, V., et al., "Low-dark current, high gain GaInAs/InP avalanche photodetectors," IEEE J. Quantum Electron., vol. QE-17, pp. 260 -264, Feb. 1981.

16 Nishida, K., Taguchi, K., and Matsumoto, Y., " InGaAsP heterostructure avalanche photodiodes with high avalanche gain," Appl. Phys. Lett., vol. 35, pp. 251 -253, 1979.

17 Smith, D. R., et al., "p-i-n/FET hybrid optical receiver for longer wavelength optical communication systems," Electron. Lett., vol. 16, pp. 69 - 70, 1980.

18 Izawa, T., Kobayashi, S., Sudo, S., and Hanawa, F., "Continuous fabrication of high silica fiber preform," 1977 IOOC, Tech. Digest pp. 375 - 378.

19 Hanawa, H., et al., "Fabrication of completely OH free VAD fiber," Electron. Lett., vol. 16, pp. 699 - 700, Aug. 1980.

20 Tomaru, S., Kawachi, M., and Edahiro, T., "Fabrication of single-mode fibers by the VAD method," Electron. Lett., vol. 16, pp. 511 - 512, June 1980.

21 Kimura, T., et al., "Coating technique for high speed drawing," 6th ECOC, Tech. Digest pp. 57 - 60, Sep. 1980.

22 Hirai, M., et al., "Melt splice of multi-mode optical fiber with an electric arc," Electron. Lett., vol. 13, pp. 123 - 124, 1977.

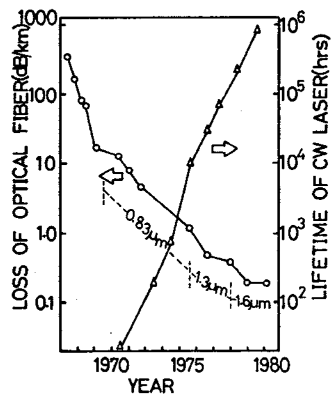

Fig. 1 Progresses in reduction of fiber loss and in lengthening of laser life time.

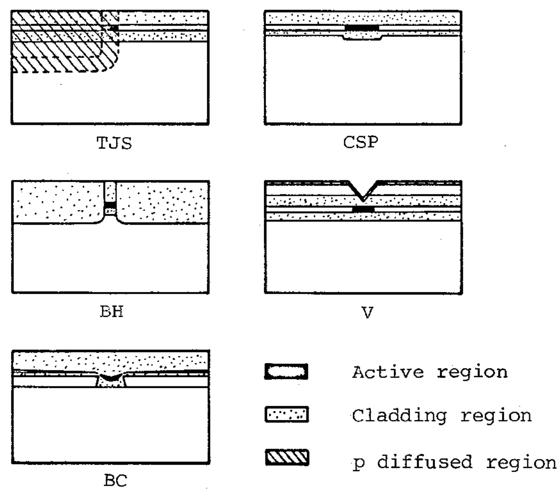

Fig. 2 Fundamental transverse mode laser structures.

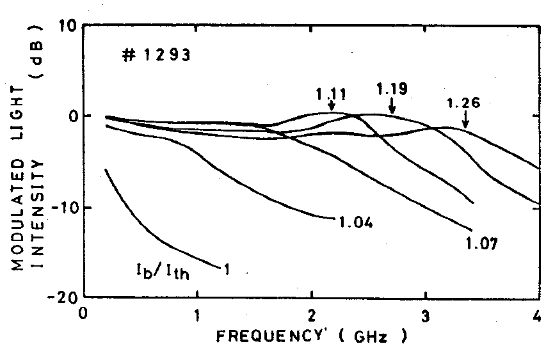

Fig. 3 Frequency modulation characteristics of a TJS laser.

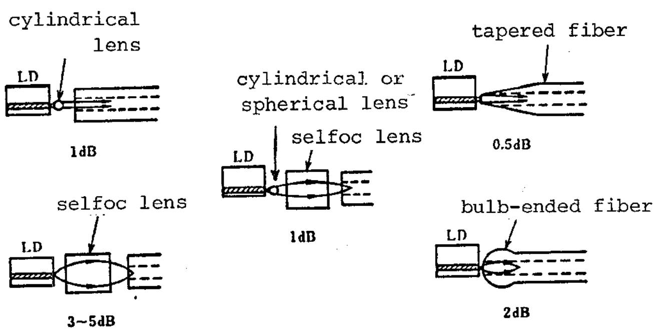

Fig. 4 Coupling methods.

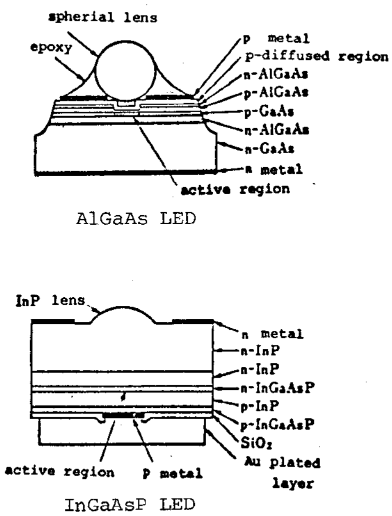

Fig. 5 LED structures.

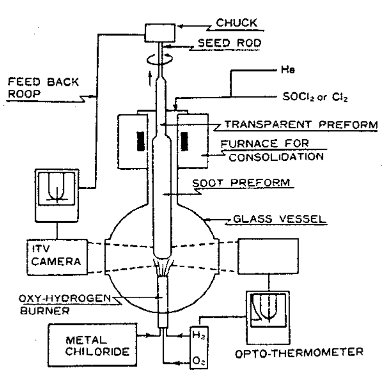

Fig. 6 Apparatus for fiber preform fabrication by VAD method.

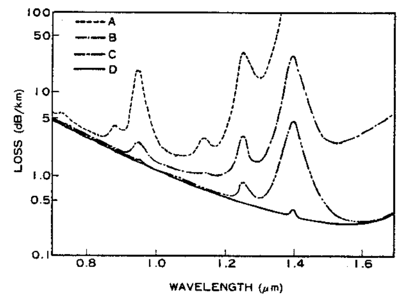

Fig. 7
Progress in reduction of loss of fibers made by VAD method. The lines denoted by A, B, C and D represent the best data in each year. (A:1977, B:1978, C:1979, D:1980)

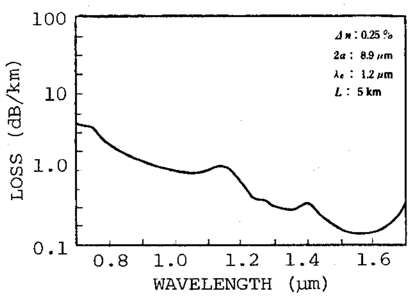

Fig. 8
Loss of a single mode fiber.

Table 1 Typical characteristics of laser diodes and LEDs.

Device		Wavelength (μm)	Power (mW)	Bandwidth (MHz)	Coupling Power* (mW)	Life Time (hr)
LED	AlGaAs	0.75 - 0.9	2	50	0.1	10^8
	InGaAsP	1.3	2	50	0.1	10^8
LD	AlGaAs	0.8 - 0.9	3 ~ 5	1000	1	10^6
	InGaAsP	1.3	3 ~ 5	1000	1	> 10^4
	InGaAsP	1.6				?

* Coupling Power to a fiber (core diameter : 60 μm, NA : 0.21)

Table 2 Comparison of detectors.

	Si-APD	Ge-APD	InGaAs/InP-APD	InGaAs-PD/FET
λ (um)	0.5-1.0	0.8-1.5	1.25	1.0-1.7
η_{max}	0.8	0.8	0.8	0.8
i_d(A)	~ 10^{-11}	~ 10^{-6}	~ 10^{-9}	~ 10^{-9}
C_j(pF)	~ 1	~ 1	~ 1	~ 2
F (M)	~3 (M=100)	~7 (M=10)	~3 (M=10)	
τ_r(ns)	0.15		0.16	0.06

Table 3 Comparison of the MCVD and VAD methods.

		VAD		MCVD	
Dimension of preform	typ.	10-20 km		2-5 km	
	max.	more than 100 km		about 10 km	
Speed of synthesis	typ.	0.4-0.7 g/min.		0.1-0.3 g/min.	
	max	2-3 g/min. possible		0.5-1.0 g/min.	
Characteristics					
minimum loss		multi-mode	single mode	multi-mode	single mode
	0.85um	2.1 dB/km	1.9 dB/km	2.1 dB/km	1.9 dB/km
	1.3 um	0.4 dB/km	0.4 dB/km	0.5 dB/km	0.4 dB/km
	1.55um	0.22dB/km	0.2 dB/km	0.3 dB/km	0.2 dB/km
O-H ion conc.		les than 1 ppb		less than 10 ppb	
band width	typ.	0.5-1.0 GHz·km		0.8-1.2 GHz·km	
	max.	6.7 GHz·km		3.5 GHz·km	