Recent Developments in Fiber Optic Devices

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Invited Paper

Abstract —**The advent of the fundamental transverse mode laser diode and low loss optical fiber has extended the wavelength range for communication systems into the optical spectrum region. The indispensable elements for the optical communication systems are light source, transmission medium, and detector. Recent developments in this area in Japan, with particular emphasis on the fundamental transverse mode laser diode and low loss quartz optical fiber, are reviewed.**

I. Introduction

In 1970, Hayashi *et al.*, of Bell Laboratories, realized an AlGaAs double heterostructure laser which operates continuously at room temperature [1]. In the same year, Kapron *et al.*, of Corning Glass Works, made a 20-dB/km loss quartz fiber by the chemical vapor deposition (CVD) method [2]. These two epoch-making technologies stimulated the research and development work on the "dream" communication, and the fiber-optic communication is now being realized in various application fields.

The "key" devices for the optical communication systems are optical source, transmission medium, and detector. Microwave technologies greatly contributed to the rapid development of the fiber-optic communication technologies.

Increase of laser lifetime expectancy and decrease of quartz fiber loss may show an advance index of the fiber-optic device technologies. Fig. 1 shows progress in reduction of quartz fiber loss and in prolonging AlGaAs laser lifetime expectancy. An estimated mean time to failure is over 10^6 h at room temperature in a fundamental transverse mode AlGaAs laser [3], and a minimum loss of fiber reaches down to 0.2 dB at 1.55 μm in a single mode fiber [4].

Most of the fiber-optic systems are developed with 0.8–0.9-μm devices using reliable AlGaAs optical sources and Si detectors. However, a great deal of recent research is emphasized on the development of long-wavelength (1.2–1.6-μm) optical sources and detectors. This is because signal propagation in quartz fibers suffers least attenuation and distortion in the wavelength range. O–H ion free vapor-phase axial deposition (VAD) method recently introduced provides an extremely low loss attenuation loss single mode fiber [5]. The attenuation loss is less than 0.5 dB/km in the wavelength range, while it is about 2 dB/km at 0.85 μm. Quartz dispersion can approach zero near 1.3 μm [6]. Notable reduction of threshold current and transverse mode stabilization in 1.3- and 1.6-μm InGaAsP lasers has been achieved recently [7]–[11]. Preliminary life tests showed stable long term operation with estimated mean time to failure over 10^5 h at 50°C [12], [13]. The remarkable progress on long-wavelength fiber-optic devices is now stimulating research and development on single mode fiber-optic systems for realizing better transmission characteristics.

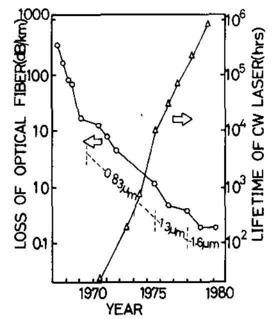

Fig. 1. Progresses in reduction of fiber loss and in lengthening of laser lifetime.

This paper describes recent developments in fiber-optic devices in Japan with particular emphasis on the fundamental transverse mode laser and low loss quartz fiber.

II. Laser

Lasers and light emitting diodes (LED's) by two kinds of materials have been developed for fiber-optic sources. The short-wavelength AlGaAs sources emitting 0.8–0.9-μm spectral bands are now widely being used. With the growing interest in the 1.2–1.6-μm bands, where the fiber loss and dispersion are low, much effort is made to develop InGaAsP sources for longer distance and higher bit-rate applications.

A. Lasing Mode and Laser Structure

The laser is constructed into double heterostructure vertically and stripe geometry along the heterostructure for reducing threshold current and controlling the lasing mode suitable for coupling to fibers. The fundamental transverse mode, essential property required for fiber-optic source, has been realized both with short-wavelength AlGaAs and long-wavelength InGaAsP lasers. Transverse mode stabilized lasers exhibit the improved characteristics such as linear light output, low operation current, high efficiency, high frequency modulation capability, and low noise. It is

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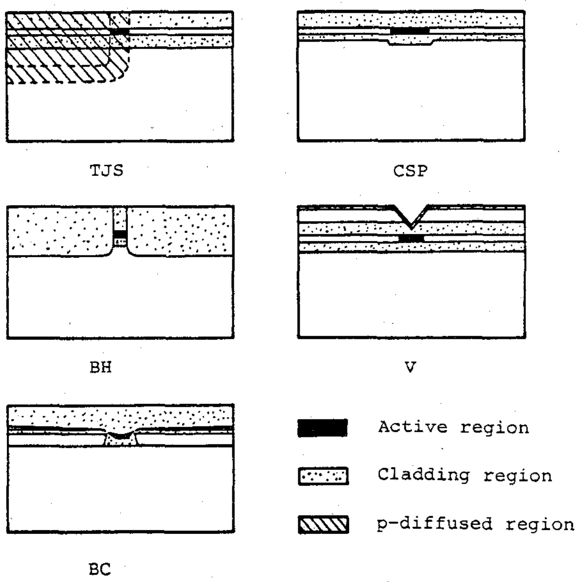

Fig. 2. Fundamental transverse mode laser structure.

essential to cutoff higher order transverse modes and to stabilize the fundamental mode for stable oscillation. The following are two approaches for mode stabilization with fundamental modes: 1) introduction of a rigid "built-in" waveguide structure; and 2) narrowing the waveguide width.

Fig. 2 shows typical stripe geometry lasers stabilized with the fundamental transverse mode. They are classified into two groups by waveguiding mechanism: 1) index-guided type [11], [14]–[20], and 2) gain-guided type. The most distinct feature between the index-guided laser and the gain-guided laser is the longitudinal mode behavior. The former shows the single longitudinal mode under dc operation as first demonstrated in AlGaAs transverse junction stripe (TJS) lasers [21]–[24] while the latter shows the multilongitudinal modes as confirmed by narrow stripe lasers such as the V-groove laser [25]–[27].

A TJS laser is introduced as an example device which lases with fundamental transverse mode and single longitudinal mode. A TJS laser is fabricated as follows [28]. On semi-insulating GaAs substrate, n layers of AlGaAs double heterojunction are grown with liquid phase epitaxy (LPE). Zn is diffused selectively and then p region is formed by heat treatment. Current flows through thin GaAs layer horizontally and carriers are injected into p region. Optical guide p region is surrounded by double heterostructure AlGaAs cladding layers, p^+ and n regions, and both mirrors.

Fig. 3 shows near field and far field patterns of a TJS laser. Beam width of the far field pattern is 10–50°, in full angle at half maximum, depending on aperture size of optical waveguide. A TJS laser has typically the aperture dimensions of 0.7 by 2 μm. A circular beam is preferable for fiber optics.

A TJS laser diode first realized the longitudinal single mode oscillation under dc operation. At present, so called index-guided lasers are recognized to oscillate in the single longitudinal mode. However, gain-guided lasers like the V-groove laser are recognized to oscillate in multilongitudinal modes in most cases. Fig. 4 shows typical lasing spectra of an index-guided TJS laser and a gain-guided V-groove laser.

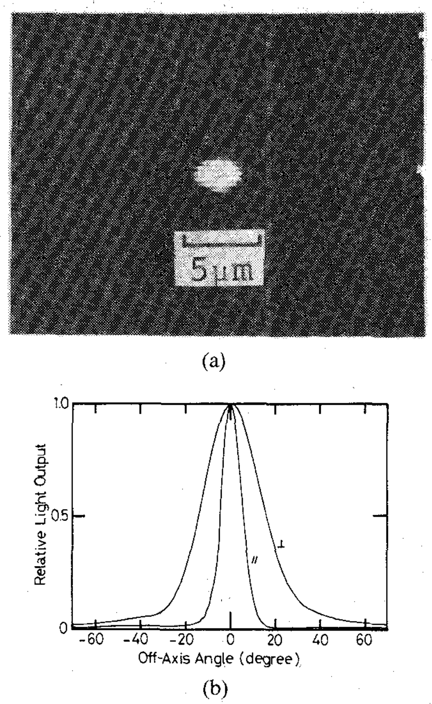

Fig. 3. (a) Near-field and (b) far-field patterns of a TJS laser.

B. Wavelength and Output

In short-wavelength 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 have a low threshold current of 15–30 mA in the wavelength range as shown in Fig. 5 [29].

Fig. 6 shows a typical light output versus current characteristic of TJS lasers [30]. Light output reaches linearly

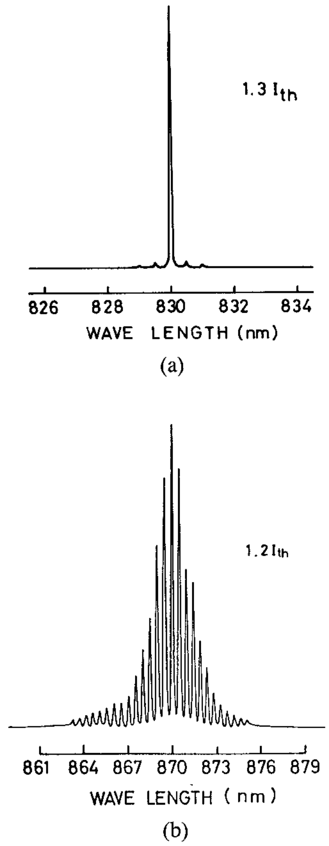

Fig. 4. Typical lasing spectra of (a) an index-guided TJS laser, and (b) a gain-guided V-groove laser.

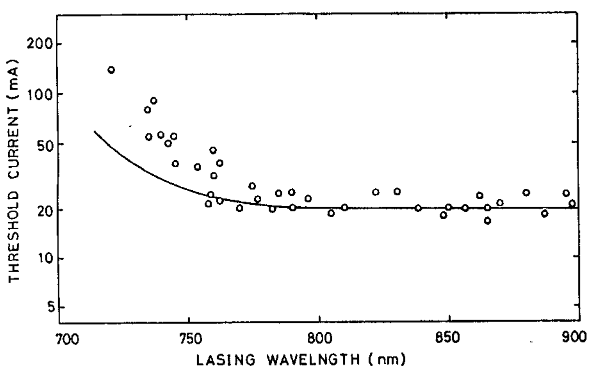

Fig. 5. Threshold current versus lasing wavelength in AlGaAs TJS lasers with different Al content in the active layer.

up to 10 mW, and is restricted by catastrophic optical damage (COD) at 15–25 mW, which corresponds to the optical power density of a few megawatts per square centimeter. TJS lasers are used practically with the light output power of 3–5 mW.

The COD occurs at the mirror surface due to intense light output density. The COD level is a few megawatts per square centimeter of the light output which corresponds to 20–50 mW for ordinary transverse mode stabilized AlGaAs lasers. Recently, a notable improvement of COD has been realized in "crank" type TJS lasers which has a COD level over 100 mW (10 MW/cm^3) [31]–[33]. The structure of the newly developed "crank" type TJS laser is shown in

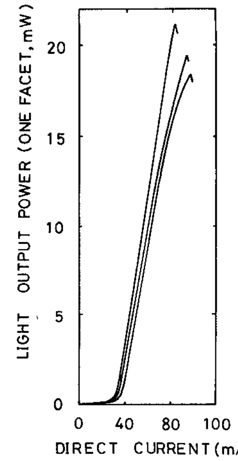

Fig. 6. Typical light output versus current in TJS lasers.

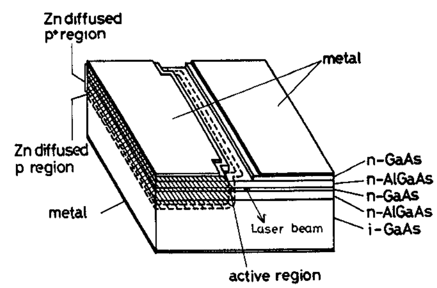

Fig. 7. Crank type TJS laser.

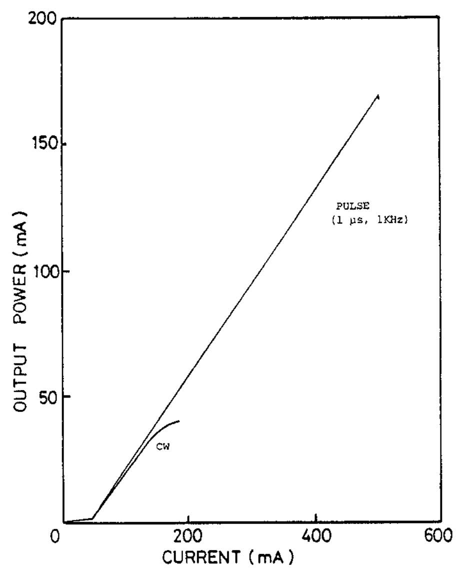

Fig. 8. Typical light output versus current for pulsed and CW operation in crank type TJS laser.

Fig. 7. Active optical waveguide is doubly bent at a right angle near the mirrors, which changes the vicinity of the mirrors of the optical waveguide into a nonactive and nonabsorbing window for the lasing light. Lasing light cannot bend abruptly, but runs straight through the nonactive region and to the mirror. Considerable increase in optical output is attained in crank TJS lasers. Output power of 120–180 mW in pulsed operation has been

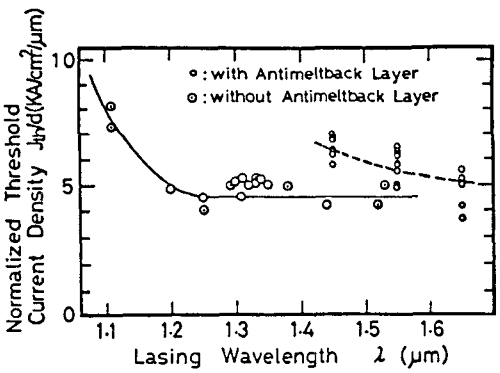

Fig. 9. Threshold current density in long-wavelength InGaAsP lasers with different compositions lattice-matched to InP.

achieved. In the case of CW operation, light output is limited by self heating not by the COD. Fig. 8 shows typical light output versus current characteristics for pulsed and CW operation. The crank TJS laser operates at temperatures as high as 90°C with a light output power more than 15 mW.

In the long-wavelength InGaAsP lasers, the lasing wavelength extends 1.2–1.6 μm with low threshold current density as shown in Fig. 9 [34]. Particular interests are emphasised on 1.3-μm lasers for wide-band transmission due to zero material dispersion of the quartz fiber, and 1.6-μm lasers for long distance transmission due to the lowest loss of the fiber. The fundamental transverse mode lasers are buried heterostructure (BH) [7]–[10] and buried crescent (BC) [11], [35]–[37] lasers with very low threshold current of 10–20 mA. COD in the long-wavelength InGaAsP lasers exceed 10 MW/cm^2, which is attributed to the material property of very low surface recombination rate for injection carriers.

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

C. Modulation

The fundamental transverse mode laser has a wide-band frequency modulation characteristics with reduced resonance-like peak.

High frequency modulation capabilities of lasers is of great importance in applications such as wide-band fiber-optic communication systems. A requirement for the wide-band laser is the suppression of the resonance-like peak in analog modulation systems, or of the relaxation oscillation in a pulse code modulation system. At data rates above 100 Mbit/s, the relaxation oscillation can produce a serious deterioration of the pulse shape. The resonance-like peak or relaxation oscillation is found to be especially pronounced in wide stripe (~10-μm) transverse mode unstabilized lasers.

Suppression of the resonance-like peak or relaxation oscillation has been observed in mode stabilized lasers and is believed to be due to lateral carrier diffusion [38], [39] and the feeding of spontaneous emission into the lasing modes [40].

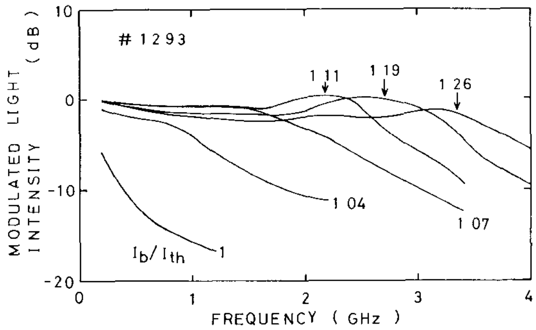

Fig 10. Modulation characteristics of a TJS laser.

The TJS laser has a very wide frequency modulation bandwidth over 4 GHz with an almost-suppressed resonance-like peak [41]. The modulation characteristics agree with a simple analytical formula derived from a small signal analysis of the single mode rate equations for carriers and photons involving the carrier diffusion [41]. The spontaneous emission rate into the lasing mode in the TJS laser is too small to influence to the modulation characteristics.

Fig. 10 shows an example of the suppression of the resonance-like peak in a TJS laser [41]. A modulation bandwidth over 4 GHz has been obtained at a bias current 1.5 times threshold with much reduced resonance-like peak.

Recently, 8-Gbit/s PCM direct modulation of a TJS laser has been reported [42]. The high frequency modulation capability of the TJS laser is due to the stable single mode oscillation and the short spontaneous lifetime by heavy doping in the active region.

D. 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" or 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-guided lasers may yield a significant detrioration of S/N ratio. The noise in gain-guided lasers can be stabilized with multimode oscillation by the mode partition effect for oscillating modes although the background noise level is much higher than that of index-guided lasers [26].

Modal noise is caused by the effect of spatial filtering on speckle patterns in fibers, when coherent laser light is launched in a multimode fiber [43]. Multilongitudinal mode lasers are suitable for this end [44], [45]. To reduce the noise by index-guided lasers, it is found useful to superimpose very high frequency modulation current to signal current so as to make the laser oscillate in multilongitudinal modes [46], [47].

E. Lifetime

The lifetime of AlGaAs lasers has been drastically improved by introducing defect-free crystal growth technique

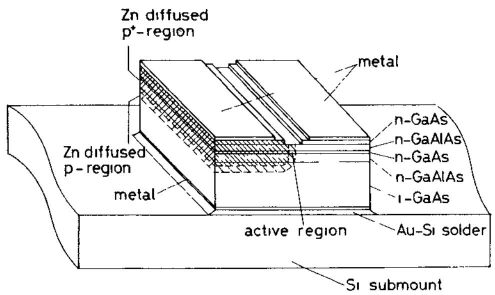

Fig. 11. Configuration of long-lived TJS laser.

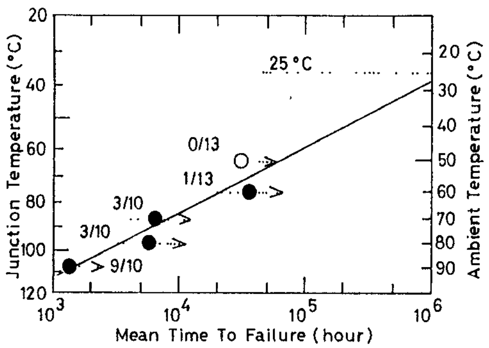

Fig. 12. Operating temperature dependence of mean time to failures in TJS lasers.

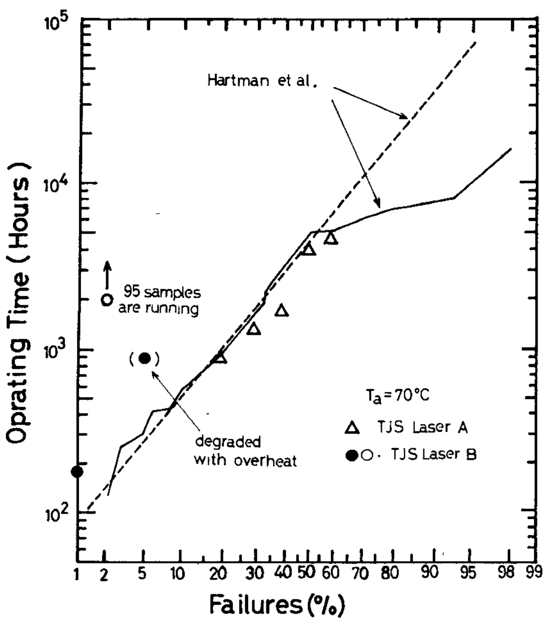

Fig. 13. Failures in TJS lasers at 70°C.

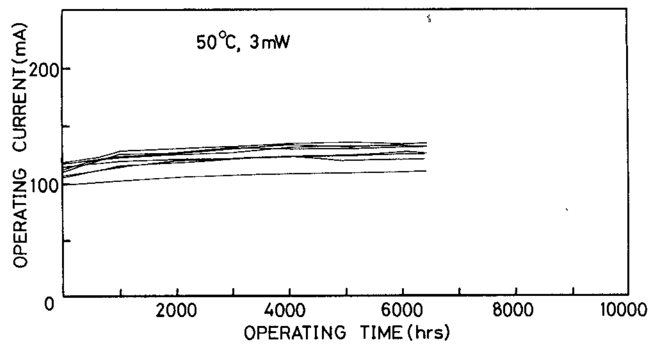

Fig. 14. Variation of operation current with operating time in InGaAsP BC lasers at 50°C with a constant light output of 3 mW/facet.

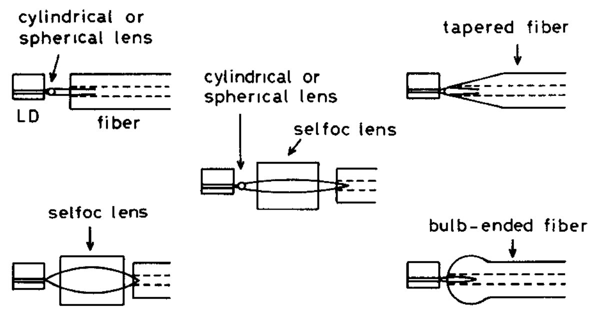

Fig. 15. Coupling methods between a laser and a fiber.

[48]–[51], dielectric film coating of the mirror surface [52]–[56] to avoid surface deterioration due to oxidation [57], and Si submount between the laser chip and the heatsink using hard solder such as Au–Si instead of In [58], [59]. An example of long-lived TJS laser structure is shown in Fig. 11 [59]. Despite a junction-up configuration, TJS lasers can operate continuously above 70°C. The maximum continuous operation by the configuration was 130°C. The junction-up configuration is easy in die-bonding and desirable for production.

Fig. 12 shows the mean time to failures at 50, 60, 70, 80, and 90°C for AlGaAs TJS lasers with a constant light output of 3 mW/facet [3], [60]. The solid line shows temperature dependence of the mean time to failures calculated with the assumption of activation energy of 1 eV, which fits well with the experimental plots. Very low failures of the TJS lasers are demonstrated in Fig. 13 [60]. There are only 3 failures out of 100 pieces at 2000 h at 70°C. These results show a mean time to failures over 10^6 h at room temperature.

Operating life of InGaAsP long-wavelength lasers has been tested and exhibit very long life expectancies [12], [13], [61]. Fig. 14 shows variation of operation current with operating time in InGaAsP BC lasers with a constant light output of 3 mW/facet [12]. It can be seen that the operation is stable after more than 5000 h.

F. 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 microlenses and the use of tapered or bulb-ended fiber pigtails as shown in Fig. 15 [62]–[64]. Coupling losses are 1–2 dB for a standard multimode fiber, while they are 5–7 dB by direct butt coupling. A new laser device with a directly attached micro-spherical lens on a TJS laser facet is developed and coupling loss of 1 dB is achieved for a standard multimode fiber [65].

Recently, coupling losses as low as 3.5 dB has been obtained for 1.3-μm lasers to a single mode fiber by the use of a microspherical lens and a graded index rod lens in conforcal arrangement [66]. The configuration is useful for

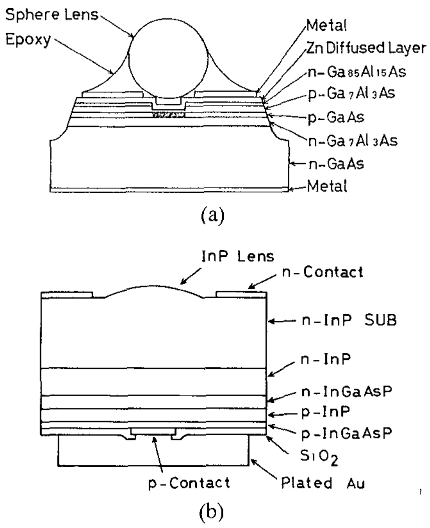

Fig. 16. Typical structures of fiber-optic LED's. (a) AlGaAs LED. (b) InGaAsP LED.

TABLE I
THE STATE-OF-THE-ART LIGHT SOURCES

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	$> 10^5$
	InGaAsP	1.6				?

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

practical use because a glass window can be inserted between the microspherical lens and the graded index rod lens, which enables us to mount a laser chip with the microspherical lens in a hermetically sealed package and provides a reliable laser package configuration for practical use.

III. Light Emitting Diode

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

LED's 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 fiber-optic LED are shown in Fig. 16. For efficient coupling, a microspherical lens is attached, with a high pure silicone regin, to the light emitting surface in a self-aligned configuration by an etched hole [67], or a monolithic hemispherical structure is formed on the light emitting surface [68].

Light output is typically several milliwatts in LED's, but since this spreads in all directions due to the spontaneous origin only a few percent is normally coupled into a typical multimode fiber. Chromatic dispersion is smaller by a factor of 15 at 1.3 μm than at 0.85 μm, which greatly extends the range of data rates if 1.3-μm long-wavelength InGaAsP LED's are used.

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 the expense of light efficiency [69].

Lifetime of LED is estimated over 10^8 h from accererating tests in short-wavelength AlGaAs and long-wavelength InGaAsP [70].

Table I shows the characteristics of the state-of-the-art lasers and LED's for fiber-optic light sources.

IV. Detector

In short-wavelength fiber-optic systems, Si p-i-n photodiode and avalanche photo-diode (APD) are well developed. Low noise and high speed Si APD has been realized in p^+-p-n planar mesa structure with eliminating carrier diffusion tail [71], [72].

In long-wavelength systems, Ge APD is used for high bit-rate and long distance applications. The performance of the device is improved in an n^+-n-p structure by design optimization of multiplication noise $F(M)$ of 7 dB has been obtained at 1.3 μm for the multiplication factor $M = 10$ [73].

Recently, a low dark-current high-gain InGaAs/InP APD was developed for the use in the 1.0–1.6-μm spectral region. The p-n junction is in the InP, so that the high-field region is in the InP while the photo-generation region is in the InGaAs [74], [75].

Another receiver design, using a low dark-current InGaAs p-i-n photodiode and a low noise GaAs FET preamplifier, offers an attractive alternative to the APD

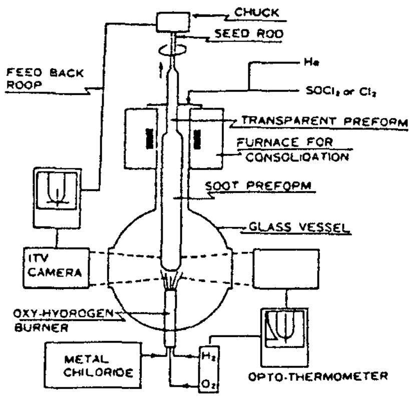

Fig. 17. Apparatus for fiber preform fabrication by VAD method.

TABLE II
THE STATE-OF-THE-ART 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

receiver at the long-wavelength transmission systems [76].

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

V. OPTICAL FIBER

Transmission characteristics of optical fiber is expressed by the attenuation loss and the bandwidth. The loss curve in relation to the wavelength is V shaped. On 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 intrinsic 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. Main subject to realize a low loss fiber was to eliminate the O–H ions.

The bandwidth is mainly limited by the multimode 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 megahertz in step-index type, a few hundreds of megahertz to a few gigahertz in graded-index type multimode fibers by optimizing the refractive index profile, and a few to a 100 GHz in single mode type.

A. MCVD Fiber

The well-known method for making preform of quartz fiber is the modified chemical vapor deposition (MCVD) method which was developed in Bell Laboratories in 1974 [77]. With use of this method, fiber loss has been reduced to ultimately low loss levels of 0.47 dB/km in 1976 [78], and 0.2 dB/km in 1979 [4]. These results show the excellent features of the MCVD method by which unexpected impurities can be reduced. However, the index dip often appears at the center of the fiber, which implies that the index profile control is not reproducible for wide-bandwidth fibers. Another problem of the MCVD method is the relatively low production speed.

B. VAD Fiber

A new VAD method has been developed at NTT in 1977 to show better performance and possible capability of mass production [79], [80].

The method is a successive production method of preform. As shown in Fig. 17, 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 tiny bubbles completely. By using helium gas as a consolidation environment, the problem was solved [81].

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 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 down 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 μm [82]–[87], which is better than that of MCVD method. Fig. 18 shows progress in reduction of loss in VAD fibers [80].

The third problem was to control the refractive index profile. It is found that the concentration of GeO_2, which

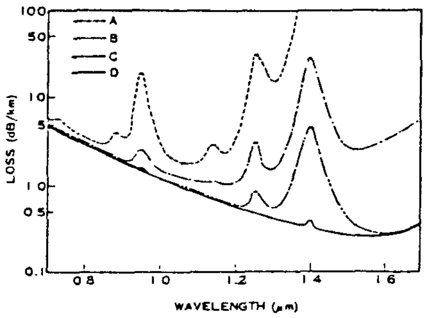

Fig. 18. Progress in reduction of loss of fibers made by VAD method [80]. The lines denoted by A, B, C, and D represent the best data in each year. (A: 1977, B: 1978, C: 1979, D: 1980)

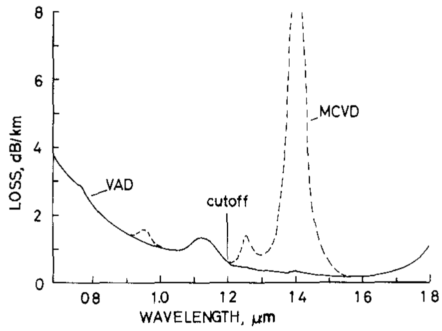

Fig. 19. Loss of a single mode VAD fiber [5]

TABLE III
COMPARISON OF VAD AND MCVD FIBERS

		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
	0.85 μm	2.1 dB/km	1.9 dB/km	2.1 dB/km	1.9 dB/km
	1.3 μm	0.4 dB/km	0.4 dB/km	0.5 dB/km	0.4 dB/km
	1.55 μm	0.22dB/km	0.2 dB/km	0.3 dB/km	0.2 dB/km
O-H ion conc.		less 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	

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 [88]. Fibers made by the method have no index dip and superior transmission characteristics. The method makes it possible to fabricate fibers with smaller index profile fluctuations, both azimuthal and axial. The maximum bandwidth of 6.7 GHz·km and average of 0.5–1 GHz·km have been obtained, which are better than the values achieved by the MCVD method [89].

The fourth problem was to make a single mode fiber. Since a considerable part of optical field spreads into cladding layer in a single mode fiber, it is necessary to purify the cladding layer as well as the core to reduce the loss. Multilayered 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 and 1.75 μm as shown in Fig. 19 [5]. Since the fiber has no center dip, bending loss is quite small.

A 100-km long fiber has been spun with a drawing speed of 120 m/min from a large preform made by the VAD method [90].

Table III shows comparison of the MCVD and VAD fibers.

C. Splicing

Two methods are known to splice fibers: butt joint method using adhesive of similar refractive index to the core; and fusion method. An arc prefusion method is to butt fiber ends preheated with an electric arc [91]. The method has advantages of smoothing scraches 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 multimode and single-mode fibers. The method enables short time splicing and is also applicable to multifiber cables [92].

VI. 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 is inferior to the microwave oscillator in coherency and stability at present. "Pure" single mode lasers for single mode fiber systems and "stable" multimode lasers for multimode fiber systems are favorable targets. Improvement of threshold current temperature dependence of long-wavelength InGaAsP lasers is a subject to be achieved.

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

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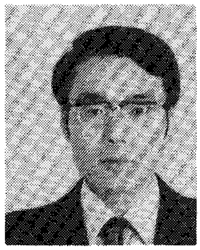

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Prediction of Laser Wavelength for Minimum Total Dispersion in Single-Mode Step-Index Fibers

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Abstract —**Pulse dispersion in single-mode optical fibers with step-index profiles has been analyzed in the past using asymptotic methods. One of these methods is based on the approximate characteristic equation for the dominant mode of propagation in these structures, obtained using the "weakly guided" condition. Other methods use approximations for certain parameters of this equation. Utilizing numerical methods of differentiation and interpolation, we have developed a method for the analysis of pulse dispersion in these fibers that is based on solutions of the exact characteristic equation. Exact formulas for the parameters necessary for this study have been established and developed to the point where the steps that would follow, involving extensive analytical effort, are replaced by computational procedures. We make comparisons between our method and those that, although based on asymptotic expressions, present the best theoretical characteristics. The differences found are discussed. This method permits greater precision in prediction of the ideal laser wavelength for use with a given single-mode optical fiber.**

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I. INTRODUCTION

DISTORTION OF pulses in single-mode optical fibers with step-index profiles results from a combination of dispersive effects that are due to the wavelength (λ) dependence of the refractive indexes of the lightguide

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