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Tatsuya Kimura (S'63–M'68–SM'78), for a photograph and biography, see p. 65 of the January 1982 issue of the JOURNAL OF QUANTUM ELECTRONICS.

Suppression of Mode Partition Noise by Laser Diode Light Injection

KATSUSHI IWASHITA AND KIYOSHI NAKAGAWA

***Abstract*—This paper describes the improvement in mode partition noise characteristics when a laser light is injected into a laser diode modulated at 400 Mbits/s. A single-mode fiber transmission experiment is carried out for the 1.5 μm region. A 20 km repeater spacing at 400 Mbit/s modulation is achieved by LD light injection. The center longitudinal mode power is increased to 94 percent of the total modes. Relative noise in the center longitudinal mode is improved 30 dB by optical injection of −18.2 dBm. However, the mode partition noise generated by noninjected modes is not completely suppressed. The relationship between the half-power width of the spectral envelope and signal-to-noise ratio (SNR) degradation is obtained at 20 km fiber length. If 3 dB excess SNR degradation is allowed for the mode partition noise, then the necessary half-power width of the spectral envelope is less than 0.6 nm.**

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I. INTRODUCTION

SILICA-based optical fiber losses have been achieved at less than 1.0 dB/km from the 1.1–1.7 μm wavelength region [1]. There is a possibility of realizing several tens of kilometers of repeater spacing in a high bit rate using these low-loss single-mode fibers. However, when we use semiconductor laser diodes (LD's) as an optical source, the repeater spacing is restricted by the mode partition noise in a high bit rate [2]–[4]. For example, 20 km repeater spacing has not been achieved at 400 Mbits/s at 1.51 μm due to the influence of mode partition noise [5]. Although 44.3 km repeater spacing has been achieved at 2 Gbits/s at 1.3 μm in the dispersion free region, narrow spectral distribution is required [6]. Thus, the mode partition noise prevents the realization of high-speed transmission and wavelength division multiplexing transmission systems. Zero dispersion in low-loss wavelengths

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[7], and single longitudinal mode oscillation [8] are the only two methods for avoiding the influence of mode partition noise.

An LD light injection technique is an effective method for operating a single longitudinal mode in a directly modulated LD. This effect is confirmed at a 100 Mbit/s transmission [8]. However, the influence of the mode partition noise is conspicuous at 400 Mbits/s or more. Therefore, it is important to estimate the optical injection effect for a high bit rate.

This paper deals with the light injection effect in an LD modulated at 400 Mbits/s. Injection power is evaluated in *I-L* characteristics. The measured noise improvement in a longitudinal mode is discussed. Finally, the effect of the LD light injection in a 400 Mbit/s single-mode fiber transmission system is made clear, and the calculated results for the relationship between the spectral distribution and signal-to-noise ratio degradation are also presented.

II. Various Characteristics of LD Light Injection

A. Measurement System

The system used to measure the LD light injection is shown in Fig. 1. Both LD's have a BH structure on a p-type InP substrate [9]. The wavelength of these LD's are adjusted by controlling the temperature and bias current. The threshold current value I_{th1} of the injection LD (LD 1) is 43 mA at 20.0°C. This LD operates under the dc operation at a single longitudinal mode of 1.5185 μm up to 79 mA, and at a single longitudinal mode of 1.5200 μm over 85 mA. The threshold current value I_{th2} of the injected LD (LD 2) is 37 mA at 20.0°C. This LD operates at a single longitudinal mode of 1.5185 μm. These LD's are set at intervals of 20 cm, and are combined optically with two lenses.

B. Current-Light Characteristics by Optical Injection

The *I-L* characteristics of the LD 2 without injection and with injection are shown in Fig. 2. The bias current is normalized by the threshold current I_{th2} and the light output by 0.66 mW at $1.4 I_{th2}$. The injection LD is biased at 70 mA under dc operation. The *I-L* characteristics of LD 2 with injection are measured as follows. When the wavelengths of both LD's coincided, the change in *I-L* characteristics became maximum. The *I-L* characteristics of the injected LD are measured by changing the injected LD temperature. The wavelength becomes longer as the temperature rises, or shorter as the bias current increases under constant temperature, due to reflective index change. Therefore, the bias current value when the wavelength of both LD's coincide increases with the injected LD temperature. The injected *I-L* characteristics are obtained by the following rate equations [10]:

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_s} - \sum_i \alpha (g_i n - N_0) S_i, \tag{1}$$

$$\frac{dS_i}{dt} = \alpha (g_i n - N_0) S_i - \frac{S_i}{\tau_p} + \beta_i \frac{n}{\tau_s} + \frac{S_{in,i}}{\tau_p} \tag{2}$$

where n is the carrier density, J is the injection current density, e is the electron charge, d is the active layer thickness, τ_s is

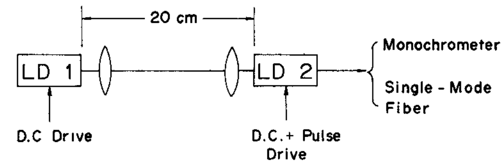


Fig. 1. Measurement system of LD light injection.

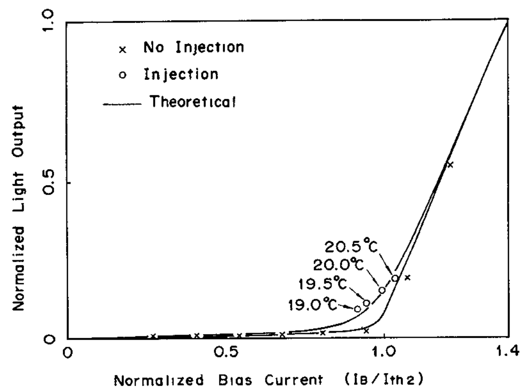


Fig. 2. Current-light output characteristics of an LD 2. Solid lines are calculated by (1) and (2). X indicates without injection. O indicates with injection.

the carrier lifetime, τ_p is the photon lifetime, α is the gain constant, g_i is the spectral gain function, N_0 is the constant relating to the energy bandgap, β_i is the fraction of spontaneous emission coupled into the longitudinal laser mode i, S_i is the photon density of mode i, and $S_{in,i}$ is the injection photon density to mode i. The spontaneous emission factor β_i and the spectral gain function are approximately given by

$$\beta_i = \frac{\beta_0}{1 + (2 \cdot i \cdot \Delta\lambda / \Delta\lambda_s)^2} \tag{3}$$

$$g_i = 1 - (2 \cdot i \cdot \Delta\lambda / \Delta\lambda_g)^2 \tag{4}$$

where $\Delta\lambda$ is the mode spacing of the longitudinal modes, $\Delta\lambda_s$ is the half-power width of the spontaneous emission, and $\Delta\lambda_g$ is the half-power width of the gain distribution. For the calculation, the LD characteristic parameters are assumed to be $\tau_s = 2$ ns, $\alpha = 5 \times 10^{-12}$ m^3/s, $N = 5 \times 10^{23}$/m^3, $\tau_p = 2$ ps, $\Delta\lambda = 1.5$ nm, $\Delta\lambda_s = 150$ nm, $\Delta\lambda_g = 100$ nm, $\beta_0 = 2 \times 10^{-4}$, and the number of modes is 201. The injection photon density distribution $S_{in,i}$ is calculated from (1)-(4) at $J_b/J_{th} = 2.0$. The solid lines in Fig. 2 are calculated from (1)-(4) at injection power −18.2 dBm and no injection. The measured value corresponds to the calculated one. This results in an injection power of −18.2 dBm.

C. Noise Measurement

In order to estimate the magnitude of the laser mode partition noise by LD only, it is necessary to obtain the variance of the longitudinal mode amplitude in modulating high-bit rate. When LD is modulated by the pulse stream, the received spectrum of one of the longitudinal modes has the line spectrum generated by the signal and the noise spectrum generated by the waveform fluctuation of a longitudinal mode. The rate of the noise level to the signal level in the received spectrum is called the noise multiple factor of the signal power in the ith longitudinal mode $a_{2,i}$. The relationship between the relative intensity of a longitudinal mode q_i and the noise multiple factor of the signal power $a_{2,i}$ is obtained by the average and variance of the photon number in a longitudinal mode considering the laser mechanism as follows [2], [4]:

$$a_{2,i} = \frac{|S(f_n)H(f_n)|^2 (1 - q_i)\chi(\xi) T_0 \Delta f}{|S(f_s)H(f_s)|^2 q_i} \tag{5}$$

$$\chi(\xi) = 1/(1 + \xi) \tag{6}$$

where $S(f)$ is the Fourier transformation of LD output waveform, $H(f)$ is the fréquency characteristics of optical receiver system, T_0 is the pulse repetitive time, Δf is the measurement bandwidth, f_n and f_s are the measured frequencies of the noise and signal, $\chi(\xi)$ is the mode partition variance coefficient, and ξ is the mode partition constant.

The mode partition constants ξ are 7-11 for Fabry-Perot type LD's [4]. As the relative intensity of a longitudinal mode becomes greater, the noise multiple factor of the signal power in its mode becomes smaller, as shown in (5). The noise multiple factor of the signal power is measured under injection. The injected LD is driven by 400.352 Mbit/s RZ (return to zero) "1,0,0" pulse streams. The bias current I_b is 27 mA and the pulse amplitude current I_p is 37 mA. A center longitudinal mode in the injected LD output is picked out through a monochrometer and received by Ge-APD. The noise multiple factor of the signal power is obtained by noise power versus signal power characteristics. The signal power is measured at 133.45 MHz and the noise power is measured at 100 MHz.

The spectrum distributions are shown in Fig. 3, and measured noise multiple factors of the signal power of the center longitudinal mode are shown in Fig. 4. The center longitudinal mode power increases from 37 percent of the total mode power to 94 percent. The noise multiple factor of the signal power of the center longitudinal mode is improved 30 dB by light injection, and the mode partition constant ξ becomes 300 from 7.2. The 30 dB improvement consists of a 14.4 dB improvement in the longitudinal mode power and a 15.6 dB improvement of the mode partition variance coefficient $\chi(\xi)$, as calculated in (6). This mode partition variance coefficient improvement is explained as follows. The mode partition constant ξ is expressed by the probability rate of spontaneous emission coupling to laser modes to stimulus emission. When light is injected into LD, part of the spontaneous emission becomes optical injection power in addition to spontaneous emission power. Therefore, the mode partition constant ξ increases. The magnitude of the improvement is estimated by the optical injection power. The relationship between the mode partition constant ξ and LD characteristic parameters is given by [4]

$$\xi = \frac{\beta_0 V \Delta\lambda_s \pi}{\alpha \tau_s 2\Delta\lambda} \tag{7}$$

where V is the volume of the active layer. The output power of the LD 2 without injection is 10 μW. The power coupling to the laser mode is $\beta_0 \Delta\lambda_s \pi / 2\Delta\lambda$ times this power. Assuming $\beta_0 = 2 \times 10^{-4}$, $\Delta\lambda_s = 150$ nm, and $\Delta\lambda = 1.5$ nm, the power

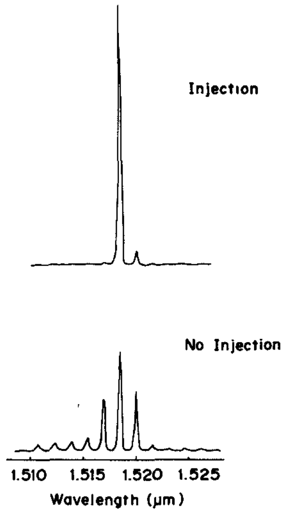


Fig. 3. Spectral distribution with and without injection.

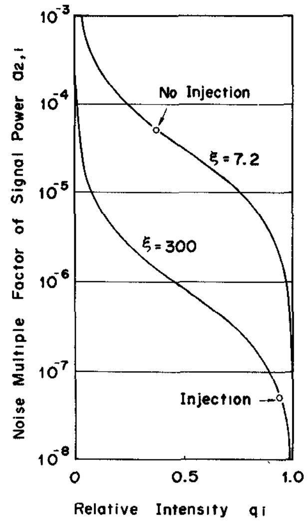


Fig. 4. Noise multiple factor of signal power with and without injection. Solid lines are calculated values from (5) for $\xi = 7.2$ and $\xi = 300$.

coupling to laser mode is 0.31 μW. In addition, as was determined in the previous section, the power coupling to the laser mode with injection is 15 μW. Since the coupling power to the laser mode becomes 48 times greater with optical injection, the mode partition constant ξ increases 48 times by injection. On the other hand, measurement of the mode partition constant ξ confirms an increase of 41.7 times by injection. The increment of the mode partition constant ξ estimated by the optical injection power corresponds very closely to the measured value.

III. Single-Mode Fiber Transmission Experiment

A. Fiber Dispersion

The injected LD output is combined with single-mode fibers by a SELFOC lens. To avoid fluctuations in the spectrum distribution caused by the reflection at the fiber end, the fiber end is obliquely polished. Consequently, the spectrum distributions do not vary with the connection. The length of the single-mode fibers used in this experiment are 16.7 and

3.6 km, each core diameter being about 10 μm. Cutoff wavelength is 1.17 and 1.25 μm, respectively, with a relative index of about 0.3 percent. The losses, including the connector and splicing connector, are 7.8 dB at 16.7 km and 9.8 dB at 20.3 km. The chromatic dispersion of these fibers are measured as follows. The bias current of the injection LD is set at 79 mA, and oscillates by only two longitudinal modes. The received waveforms for 20.3 km and the spectrum distribution are shown in Fig. 5. The received waveforms are divided into two by chromatic dispersion and their intervals are about 450 ps. The wavelengths are 1.5185 and 1.5200 μm, the interval of longitudinal modes is 1.5 nm. Therefore, the chromatic dispersion is 15 ps/km · nm. The obtained chromatic dispersion is in good agreement with the calculated one.

B. Transmission Experiment

When LD oscillates at multilongitudinal modes, the noise level of the received point is increased by mode partition noise. The injected LD is modulated at 400.352 Mbit/s "1,0,0" pulse streams and its operating condition is the same that mentioned in Section II. The noise level difference between the transmission point and the received point is measured for a 20.3 km fiber length at −33 dBm received optical power. The frequency dependence of the noise increment is shown in Fig. 6. To suppress the influence of the far-end reflection, the gaps of the connectors are filled with glycerine having 1.47 reflective index. Since the coupling loss of the single-mode fiber end and LD is over 10 dB and fiber loss is 9.8 dB; the far-end reflection power is considered to be sufficiently lower than the injection power. Therefore, the periodic noise increment generated by the far-end reflection is not observed. The noise increment in the vicinity of 300 MHz is 19.5 dB without injection, and 3 dB with injection. The dashed lines are the noise increments which are calculated by the mode partition constant ξ and the spectral distribution shown in Fig. 3, where the bandwidth is 30 kHz, the signal level is 69 dB greater than the noise level (shot noise + thermal noise), and the transmission waveform is assumed to be rectangular. The reasons for the difference between the calculated and measured values without injection are that the mode partition constants in all longitudinal modes are assumed equal, and the waveform of the LD light output is assumed to be rectangular. However, there is an inexplicable noise difference with injection. The difference between the calculated value and the measured one is 2 dB. It is considered that the noise in the center longitudinal mode is suppressed by optical injection, but the other modes are not suppressed by optical injection because the injection power is small. Therefore, the mode partition constant of the center longitudinal mode is considered to be inconsistent with that of the other longitudinal modes. In order to calculate the mode partition noise, we assume the variance of the received waveform to be as follows:

$$\sigma_m^2(t) = \sum_i \sigma_{m,i}^2(t)$$

$$= \sum_i \chi(\xi_i)\, q_i \left\{ r(t + i\tau) - \left(\sum_k q_k r(t + k\tau) \right) \right\}^2. \qquad (8)$$

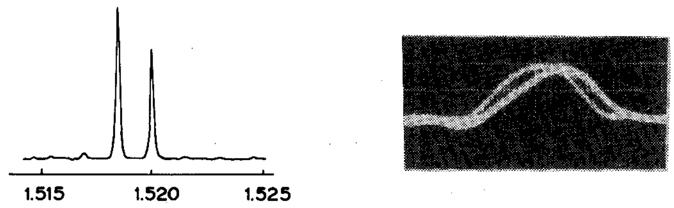


Fig. 5. Spectral distribution and received waveform (500 ps/div) for 20.3 km fiber length.

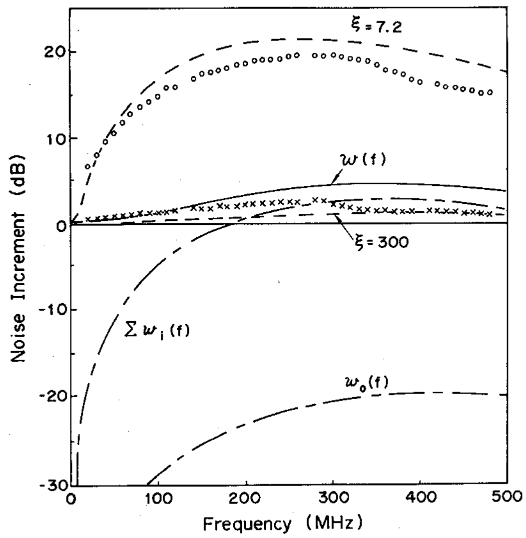


Fig. 6. Noise increment by mode partition noise. Solid line and dashed-dotted lines are calculated by (9). Broken lines are calculated by (2). X indicates with injection. O indicates without injection.

The received noise spectrum is obtained by the Fourier transformation of (8)

$$w(f) = \sum_i w_i(f)$$

$$= \sum_i \chi(\xi_i)\, q_i \left| e^{j\omega i\tau} - \left(\sum_k q_k e^{j\omega k\tau} \right) \right|^2 |R(f)|^2 \qquad (9)$$

where $\chi(\xi) = 1/(1 + \xi)$, $\tau = m \cdot \Delta\lambda \cdot L$, m is the chromatic dispersion coefficient, W is the half-power width of the spectral envelope, L is the fiber length, and $r(t)$ is the isolated waveform.

The mode partition noise is calculated from (8) and (9). The mode partition constant ξ of the center longitudinal mode is 300. The mode partition constants ξ of the other longitudinal modes are 52, which are calculated by the relative intensity and noise multiple factor of the signal power at 1.5200 μm. The solid line in Fig. 6 shows the total noise increment calculated by (9). The total noise increment is in good agreement with the measured value. The noise increment which is generated by the mode i is indicated by $w_i(f)$. The noise of the non-injected mode $\Sigma_{i \neq 0}\, w_i(f)$ is 20 dB greater than that of the injection mode. When the repeater spacing is short, i.e., $m \cdot L \cdot W/T_0$ is small, the noninjected mode power contributes to the signal. However, when the repeater spacing is long, i.e., $m \cdot L \cdot W/T_0$ is large, the noninjected power becomes noise. Therefore, it is clear that the main factor in degradation is the mode partition noise made by the noninjected mode.

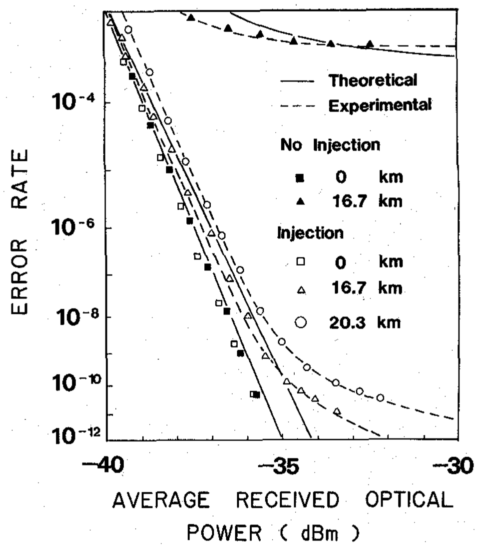
This fact is understood from experiments. The noise level is 73 dB lower than the signal level. This is because the noise multiple factor of the signal power is 5×10^{-8} as shown in Fig. 4. The noise level generated by the mode partition noise is equal to the shot noise level in the vicinity of 300 MHz. Since the mode partition noise generated by the center longitudinal mode is 4 dB less than the shot noise or thermal noise level for maximum degradation, it is clear that the degradation is dominated by the mode partition noise of the noninjected mode.

Injected LD is modulated at a 400 Mbit/s pseudorandom pulse pattern with a 50 percent mark density. Its output is transmitted by single-mode fiber. The error-rate characteristics at a 20.3 km fiber length are influenced by the bias current of the injection LD (LD 1). In low bias current, the error-rate characteristics degrades due to the reduction of the optical injection power. In high bias current, the error-rate characteristics degrade due to the wavelength shift of the injection LD. The bias current achieving the error rate under 10^{-8} at -32 dBm is from 61–73 mA. Error-rate characteristics and the eye-diagram with a 70 mA bias current of the injection LD are shown in Fig. 7. The spectral distribution change is the same as shown in Fig. 3. The half-power width of the spectral distribution becomes from 3.5 to 0.8 nm. The concentration of the center longitudinal mode power becomes 37–94 percent of the total modes. Error-rate characteristics without injection appear with floor characteristics for 16.7 km due to the mode partition noise. Average received optical power degradation for 0 km at error-rate 10^{-11} with injection is 2 dB at 16.7 km and 4.5 dB at 20.3 km. Error-rate characteristics at 0 km fiber length are not influenced by optical injection. Extinction ratio degradation and variance in optical waveform has been reported in the light injection experiment. However, the optical waveform is not influenced by the injection. Since the extinction ratio obtained by the static characteristics shown in Fig. 2 is 19 dB, extinction ratio degradation by injection is negligible.

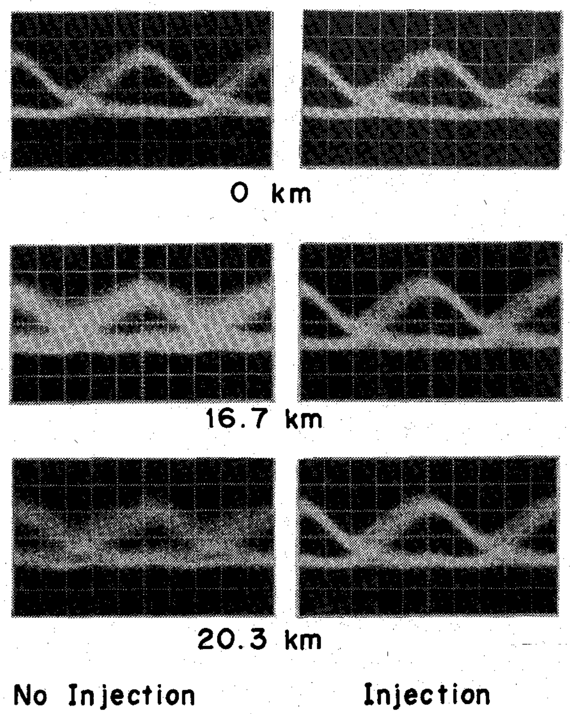
Signal-to-noise ratio (SNR) considering the mode partition noise is given by

$$\mathrm{SNR} = -20 \log \frac{\sqrt{\sigma_t^2 + \sigma_{s,1}^2 + \sigma_{m,1}^2} + \sqrt{\sigma_t^2 + \sigma_{s,0}^2 + \sigma_{m,0}^2}}{2S_{0-p}(1-2I)} \tag{10}$$

where σ_t^2 is thermal noise variance, $\sigma_{s,1}^2$ and $\sigma_{s,0}^2$ are shot noise variance for marked and space levels, $\sigma_{m,1}^2$ and $\sigma_{m,0}^2$ are the variance of the mode partition noise for marked and space levels, S_{0-p} is signal height, and I is the intersymbol interference. The solid lines in Fig. 7 indicate the calculated value from (10). For calculation, the output waveform is assumed Gaussian and the equalizer has Gaussian characteristics with 320 MHz bandwidth. Measured value with injection degrades from the calculated one for the following reason. When LD is a modulated random pattern, the active layer temperature is changed by each pulse stream. Since temperature change causes the wavelength change, the injection power



(a)



(b)

Fig. 7. (a) Error-rate characteristics and (b) eye-diagram (500 ps/div). Solid lines are calculated by (8) and (10). ■ indicates 0 km without injection. ▲ indicates 16.7 km without injection. □ indicates 0 km with injection. △ indicates 16.7 km with injection. ○ indicates 20.3 km with injection.

in LD 2 decreases effectively. Therefore, as the mode partition constant decreases, mode partition noise increases, and SNR degrades.

The half-power width of the spectral envelope dependence of signal-to-noise ratio degradation at 20 km fiber length is shown in Fig. 8. For the calculation, the average received optical power is -33 dBm, the SNR level without the mode partition noise is 33.5 dB, and the spectral distribution is Lorentzian. If 3 dB excess SNR degradation is allowed for the mode partition noise, the indispensable half-power width of the spectral envelope becomes less than 0.6 nm.

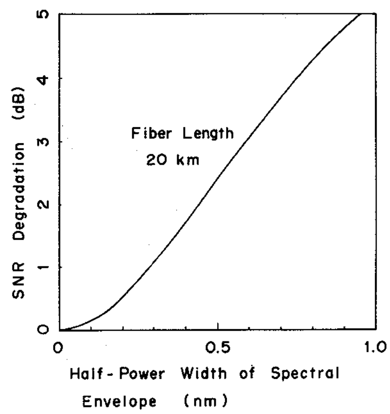


Fig. 8. Signal-to-noise ratio (SNR) degradation by mode partition noise. Solid line is calculated by (10).

IV. Conclusion

A laser diode light injection technique employing a 400 Mbit/s modulated LD that significantly suppresses mode partition noise was presented. The conclusions are summarized as follows.

Relative noise of the center longitudinal mode was suppressed 30 dB by injection. This improvement is achieved by the improvement of both the mode partition constant and signal power. The mode partition constant was improved 15.6 dB. It was shown that mode partition constant improvement can be estimated by the optical injection power.

A single-mode fiber transmission experiment at 400 Mbits/s was carried out for the 1.5 μm region. Although center longitudinal mode power is increased to 94 percent of the total modes and the relative noise in the center longitudinal mode is improved 30 dB by injection, mode partition noise was not completely suppressed. Average received optical power degradation for 0 km at error-rate 10^{-11} was 2 dB at 16.7 km and 4.5 dB at 20.3 km. It was clarified that the main factor of this degradation is the mode partition noise which is generated by noninjection modes. The relationship between the half-power width of the spectral envelope and the signal-to-noise ratio degradation was obtained for a 20 km fiber length. If 3 dB excess SNR degradation is allowed for the mode partition noise, then the necessary half-power width of the spectral envelope becomes less than 0.6 nm.

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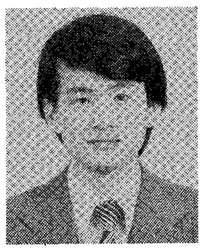

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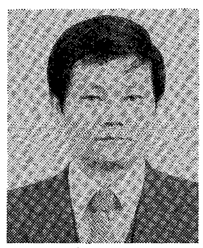

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