Laser Mode Partition Noise in Lightwave Systems Using Dispersive Optical Fiber

Robert H. Wentworth, George E. Bodeep, and Thomas E. Darcie

***Abstract*— It is well known that semiconductor laser mode partition noise (LMPN) can impair the performance of high-speed digital communication links. LMPN can also impair analog optical systems, and this phenomenon has not previously been well-characterized. In this paper we present theoretical expressions for the noise spectra that result when light from a nearly single-mode or strongly multimode semiconductor laser is passed through a length of dispersive optical fiber. These results are tested experimentally. A widely used model is found to greatly overestimate the partition noise of a DFB laser; a model for the strongly multimode case is found to match experimental results for a multimode laser. It is observed that partition noise can be significant even for multimode lasers operating near the fiber dispersion minimum.**

I. Introduction

The performance of lightwave system can be adversely effected by fiber reflection [1]–[4] and laser mode partition noise (LMPN) [5]. LMPN, which is known to be an important noise source in high-speed digital systems, can also be a problem in 1.3- and 1.55-μm analog systems using multimode or nearly single-mode (e.g., DFB) lasers with weak side modes. In this paper we derive expressions for the intensity noise spectra due to LMPN for a nearly single-mode laser and a strongly multimode laser. These spectra are compared to experimental data obtained using DFB and multimode lasers in a system containing 10 km of single-mode fiber.

"Laser mode partitioning" refers to the tendency for optical power to distribute itself between different optical modes of a laser in such a way that the power in individual modes fluctuates but the total power in all modes is relatively steady. Semiconductor lasers are subject to mode partitioning because different optical modes compete for the same gain. Partitioning becomes a problem when dispersive propagation delays cause the fluctuations in the powers of individual modes to become separated in time, so that at a given time the fluctuations of various modes no longer cancel one another.

II. Generic LMPN Noise Spectrum

Let us compute the spectrum of the noise at the output of a dispersive fiber illuminated by a CW laser subject to mode partitioning.

Manuscript received February 11, 1991; revised August 1, 1991.
The authors are with AT&T Bell Laboratories, Crawford Hill Laboratories, Holmdel, NJ 07733.
IEEE Log Number 9103475.

Given that optical power at the input to the fiber has the form

$$I_{in}(t) = \sum_m S_m(t) \tag{1}$$

where $S_m(t)$ is the power in mode m, the power at the fiber output will be

$$I_{\text{out}}(t) = \sum_m S_m(t - \varepsilon_m). \tag{2}$$

Here ε_m is the group delay of mode m. Fiber attenuation is assumed to be the same for all modes, and has been omitted from $I_{out}(t)$. It is assumed that dispersion is too small to significantly distort the signal carried by a single mode, but is large enough to potentially separate in time the signals carried by different modes.

The dispersion D_λ may be defined by

$$D_\lambda = \frac{d\varepsilon(\lambda)}{d\lambda} = \sigma L_{\text{fiber}} \tag{3}$$

where $\varepsilon(\lambda)$ is the group delay, λ is the wavelength, σ is the dispersion coefficient, and L_{fiber} is the length of the fiber. If the dispersion is nearly constant over the laser spectrum, and if the laser modes have an approximately uniform wavelength spacing $\Delta\lambda$, then

$$\varepsilon_m \approx \varepsilon_0 + m\Delta\varepsilon \tag{4}$$

where

$$\varepsilon_0 = L_{\text{fiber}}/\nu_{g0} \tag{5}$$

$$\Delta\varepsilon = \sigma L_{\text{fiber}} \Delta\lambda \tag{6}$$

and where ν_{g0} is the group velocity of mode 0. Note that (4) need not apply if different transverse or polarization modes are taken to be involved in mode partitioning. The assumptions implicit in (4) will not be invoked in what follows until the case of a strongly multimode laser is analyzed.

For a laser subject to mode partitioning, the total intensity noise will typically be small compared to the partition noise manifest at the output of a long dispersive fiber. Hence, the total optical power is taken to be equal to a constant, I_{tot}, and the power in one mode (arbitrarily taken to be mode 0) can be expressed in terms of the power in the remaining modes

$$S_0 = I_{\text{tot}} - \sum_{m \neq 0} S_m(t). \tag{7}$$

It follows that

$$I_{\text{out}}(t) - \overline{I}_{out} = \sum_{m \neq 0} \{ [S_m(t - \varepsilon_m) - \overline{S}_m(t)] - [S_m(t - \varepsilon_0) - \overline{S}_m] \} \quad (8)$$

where $\overline{I}_{\text{out}} = I_{\text{tot}}$ is the mean of $I_{\text{out}}(t)$, and $\overline{S}_m$ is the mean of $S_m(t)$ (which is assumed to be a stationary random process). Hence, the autocovariance of $I_{\text{out}}(t)$ is

$$\begin{aligned} &Cov[I_{\text{out}}(t), I_{\text{out}}(t + \Delta t)] = \\ &\overline{[I_{out}(t) - \bar{I_{out}}] \cdot [I_{out}(t + \Delta t) - \bar{I}_{out}]} \\ &= \sum_{m \neq 0} \sum_{n \neq 0} \{ Cov[S_m(t - \varepsilon_m), S_n(t + \Delta t - \varepsilon_n)] \\ &- Cov[S_m(t - \varepsilon_m), S_n(t + \Delta t - \varepsilon_0)] \\ &- Cov[S_m(t - \varepsilon_o), S_n(t + \Delta t - \varepsilon_n)] \\ &+ Cov[S_m(t - \varepsilon_0), S_n(t + \Delta t - \varepsilon_0)] \}. \end{aligned} \quad (9)$$

By the Wiener–Khinchin theorem [6], the (two-sided) spectrum of the intensity noise at the fiber output, $G_{\text{out}}(f)$, is the Fourier transform of the autocovariance of $I_{\text{out}}(t)$. Using the convention

$$F[h(\Delta t)] = \int_{-\infty}^{\infty} h(\Delta t) e^{i2\pi f \Delta t} \, d\Delta t \quad (10)$$

for the Fourier transform, $G_{\text{out}}(f)$ is

$$\begin{aligned} G_{\text{out}}(f) &= \sum_{m \neq 0} \sum_{n \neq 0} G_{mn}(f) \\ &\cdot [e^{i2\pi(\varepsilon_n - \varepsilon_m)f} - e^{-i2\pi(\varepsilon_m - \varepsilon_0)f} \\ &- e^{i2\pi(\varepsilon_n - \varepsilon_0)f} + 1] \\ &= 4 \sum_{m \neq 0} \sum_{n \neq 0} G_{mn}(f) e^{i\pi(\varepsilon_n - \varepsilon_m)f} \\ &\cdot \sin[\pi(\varepsilon_m - \varepsilon_0)f] \sin[\pi(\varepsilon_n - \varepsilon_0)f] \end{aligned} \quad (11)$$

where

$$G_{mn}(f) = F\{Cov[S_m(t), S_n(t + \Delta t)]\} \quad (12)$$

is the noise cross-spectral density of the intensity in modes m and n.[1] This result for $G_{\text{out}}(f)$ is general: it only depends on the assumption that total intensity noise is negligible.

III. Spectrum for a Nearly Single-Mode Laser

The noise spectrum $G_{\text{out}}(f)$ can be calculated more explicitly in a number of special cases. We first consider the case of a laser with one strongly dominant mode.

Following Henry *et al.* [7], we note that the gain seen by a weak side mode is nearly constant in time, so that the complex field amplitude, $\beta_m(t)$, for such a mode evolves as

$$\frac{d}{dt} \beta_m(t) = -\frac{\beta(t)}{2\tau_m} + F_m(t) \quad (13)$$

[1] Note that the restrictions $m \neq 0$ and $n \neq 0$ could be omitted from (11) since the excluded terms are each equal to zero.

where

$$\tau_m = \overline{S}_m / R = Y_m \tau_0 \quad (14)$$

where

$$Y_m = \overline{S}_m / \overline{S}_0 \quad (15)$$

$$\tau_0 = \overline{S}_0 / R. \quad (16)$$

Here, R is the spontaneous emission rate (per mode), and $F_m(t)$ is a Langevin noise term due to spontaneous emission, and Y_m is the mode suppression ratio for mode m.

Note that the model described by (13)–(16) is in part equivalent to saying that 1) the complex electric field in each side-mode is a gaussian noise process, and 2) the power in each side-mode is randomly distributed according to an exponential probability density function. This exponential distribution has been demonstrated experimentally in a number of cases [8], [9].

Since fluctuations in gain (which would otherwise couple mode amplitudes) are ignored, $\beta_m(t)$ and $\beta_n(t)$ will be independent when $M \neq n$, $m \neq 0$, and $n \neq 0$. The Appendix shows that (13) leads to

$$G_{mn}(f) = \frac{2\tau_m \overline{S}_m^2 \delta_{mn}}{1 + (2\pi f \tau_m)^2} \qquad m \neq 0, \, n \neq 0. \quad (17)$$

Thus, the intensity noise spectrum for mode m has a Lorentzian rolloff, with a half-power frequency of $(2\pi\tau_m)^{-1}$.

Substituting (17) into (11), and converting to (one-sided) relative intensity noise, we find

$$\begin{aligned} \text{RIN}(f) &= 2G_{\text{out}}(f)/I_{\text{out}}^2 \\ &= 4 \sum_{m \neq 0} Y_m^2 \left[\frac{4\tau_m}{1 + (2\pi\tau_m f)^2} \right] \sin^2 [\pi(\varepsilon_m - \varepsilon_0)/f]. \end{aligned} \quad (18)$$

For reference, recall that Y_m is the relative strength of mode m, ε_m is the dispersive delay, and τ_m is a characteristic fluctuation time expressible in terms of the spontaneous emission rate. The time τ_m could also be determined directly through an experiment capable of observing the intensity noise spectrum of mode m alone.

The noise spectrum described by each term in (18) has nulls at integer multiples of the frequency $1/(\varepsilon_m - \varepsilon_0)$. In the time domain, this reflects the fact that for every fluctuation in the side mode, there is a perfectly anticorrelated fluctuation in the main mode which is displaced in time by a relative delay $(\varepsilon_m - \varepsilon_0)$. In converting the total power (which sums main and side-mode powers) to the frequency domain, one multiplies the time-domain signal by a sinusoid at the frequency of interest, and then integrates to get a Fourier amplitude. For sinusoids at frequencies which are multiples of $1/(\varepsilon_m - \varepsilon_0)$, the side-mode fluctuation and the anti-correlated relatively delayed main-mode fluctuation receive equal weights when they are multiplied by the sinusoid; as a result, their effects cancel out and the Fourier amplitude at these frequencies is zero. At other frequencies the Fourier sinusoid weights the fluctuations and counter-fluctuation unequally so that cancellation is incomplete and there is a nonzero noise amplitude; the result is a spectrum with periodic nulls.

IV. Spectrum for a Strongly Multimode Laser

The partitioning of multimode lasers is in general difficult to describe analytically. However, simple results can be obtained when all modes are assumed to have the same average power. In particular, specializing the results of [10] yields

$$G_{mn}(f) = \frac{M\delta_{mn} - 1}{(M+1)} \left[\frac{2\tau_0}{1 + (2\pi\tau_0 f)^2} \right] \frac{I_{\text{tot}}^2}{M^2} \tag{19}$$

where M is the number of modes and

$$\tau_0 = \frac{I_{\text{tot}}}{MR}. \tag{20}$$

This expression for τ_0 is consistent with (16) since $\overline{S}_0 = I_{\text{tot}}/M$. While the assumption that all modes have equal power is clearly inaccurate, it should permit a semiquantitative estimate of the noise level likely to be observed in systems using strongly multimode semiconductor lasers.

Because mode intensities are correlated in the strongly multimode case, the summation in (11) would in general include $(M-1)^2$ terms. To facilitate combining these terms, we assume (4) applies (thus accounting only for different longitudinal modes and assuming uniform dispersion). Substituting (19) into the exponential form of (11), we sum over M modes with indexes 0 to $M-1$. Collapsing the sums using the formula for the sum of a geometric series, and doing some additional tedious simplification, we find

$$\text{RIN}(f) = \frac{1}{M+1} \left[1 - \frac{\sin^2(\pi M \Delta\varepsilon f)}{M^2 \sin^2(\pi \Delta\varepsilon f)} \right] \cdot \left[\frac{4\tau_0}{1 + (2\pi\tau_0 f)^2} \right]. \tag{21}$$

As in the previous section, the result is expressed in terms of the (one-sided) relative intensity noise. For reference, M is the number of modes, $\Delta\varepsilon$ is the dispersive delay between any two adjacent modes, and τ is a time constant related to the spontaneous emission rate or, alternatively, to the width of the intensity noise spectrum of an individual mode.

The noise spectrum in this case also exhibits nulls, this time at frequencies which are integer multiples of $1/\Delta\varepsilon$. Whenever a fluctuation occurs in one mode, this is compensated for by the aggregate of fluctuations in other modes. These compensating fluctuations are delayed relative to one another by integer multiples of $\Delta\varepsilon$; for Fourier sinusoids at frequencies at multiples of $1/\Delta\varepsilon$, various correlated fluctuations are weighted equally, so they cancel, resulting in periodic nulls in the spectrum—just as in the nearly single-mode case.

For comparison, let us calculate the signal transmission characteristics of this system. Suppose the noise-averaged input signal has the form

$$\overline{I}_{\text{in}}(t) = \text{Re}\left[I'_{\text{in}} e^{-i2\pi f t}\right] \tag{22}$$

with average modal power given by

$$\overline{S}_m(t) = \text{Re}\left[I'_{\text{in}} e^{-i2\pi f t}/M\right] \tag{23}$$

and the output signal has the form

$$\overline{I}_{\text{out}}(t) = \text{Re}\left[I'_{\text{out}} e^{-i2\pi f t}\right]. \tag{24}$$

It may be shown that the signal transfer function (neglecting optical attenuation) is

$$\left| \frac{I'_{\text{out}}}{I'_{\text{in}}} \right|^2 = \frac{\sin^2(\pi M \Delta\varepsilon f)}{M^2 \sin^2(\pi \Delta\varepsilon f)}. \tag{25}$$

Thus the signal response is maximal at frequencies where the LMPN is minimal. This is sensible insofar as good signal transmission and good mode-fluctuation cancellation both require the signals carried by all modes to be in phase with one another.

A practical result of (25) is that in order to achieve adequate signal transmission systems will generally operate at frequencies smaller than $1/(M\Delta\varepsilon)$.[2] In this regime the LMPN will be small compared to its maximal value, $\text{RIN}_{\text{max}} = 4\tau_0/(M+1)$.

In applying (21) to predicting the LMPN from a real multimode laser, one difficulty is deciding what value of M is appropriate given the laser spectrum. While the full-width at half-maximum number of modes or something similar might be used, it has been speculated that for some noise calculations an effective number of modes should be calculated according to [10]

$$M_{\text{eff}} = \left[\sum_m \left(\overline{S}_m / I_{\text{tot}}\right)^2 \right]^{-1}. \tag{26}$$

We shall make use of this formula for mode number though it is not clear whether or not it provides an optimal estimate. Our theoretical results do not depend sensitively on mode number.

V. Experiment

The detected noise spectrum for 1.55-μm multimode and nearly single-mode lasers were obtained using high-speed InGaAs p-i-n photodiode and microwave spectrum analyzer. The system used consisted of 10 km of standard single-mode fiber with a loss of 0.25 dB/km and nominal dispersion of 17 ps/nm km. Each laser was coupled to the fiber using a lensed fiber that was fusion-spliced to a optical isolator. A 500-MHz subcarrier was applied to the laser through a microwave bias-tee, resulting in a modulation depth of 4.5%. Since the LMPN was the dominant noise source, a carrier-to-noise measurement could be used to determine the LMPN.

The optical spectrum of the nearly single-mode laser (insert of Fig. 1) shows a strong side mode, 6 dB below the main mode and 1.7 nm away. Based on the CNR measurement (Fig. 1) the effective intensity noise at 500 MHz is -128 dB (1 Hz). The theory predicts a dip in the LMPN at a frequency $1/(\varepsilon_m - \varepsilon_0)$ (3.4 GHz based on the nominal dispersion) and such a dip is observed roughly 3.75 GHz. The discrepancy in locations is attributed to uncertainty in the dispersion value.

The noise spectrum predicted by (18) and the measured RIN are shown together in Fig. 2. The theoretical curve is based on $1/(\varepsilon_m - \varepsilon_0) = 3.75$ GHz and $1/(2\pi\tau_m) = 200$ MHz. These parameter values were chosen so as to roughly match the peak locations and fall-off characteristics of the theoretical

[2] There are in principle transmission windows at frequencies which are multiples of $1/(M\Delta\varepsilon)$; however, these windows are likely to be at frequencies too high to be of interest for most purposes.

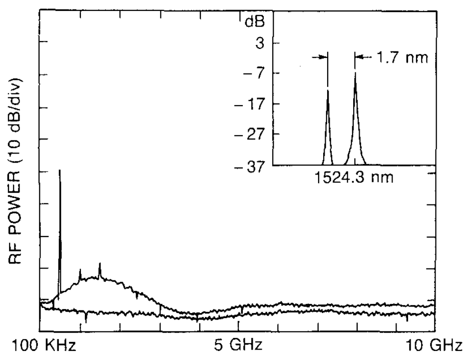


Fig. 1. RF spectrum for case where light from a nearly single-mode laser is detected after 10 km of fiber. Upper curve is for a 500-MHz subcarrier with modulation depth $m = 0.041$. Lower curve is detector noise. The noise bandwidth was 3 MHz. Inset is optical spectrum.

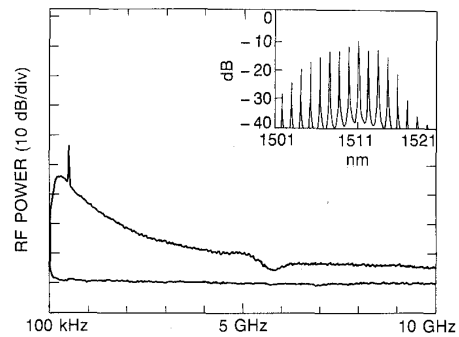


Fig. 3. RF spectrum for case where light from a strongly multimode laser is detected after 10 km of fiber. Upper curve is for a 500-MHz subcarrier with $m = 0.045$. The noise bandwidth was 3 MHz.

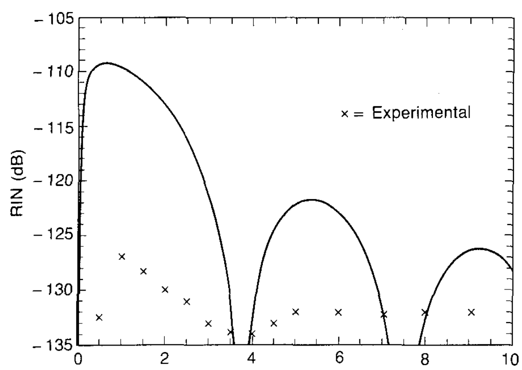


Fig. 2. Relative intensity noise: theory (for nearly single-mode case) and experiment (data abstracted from Fig. 1).

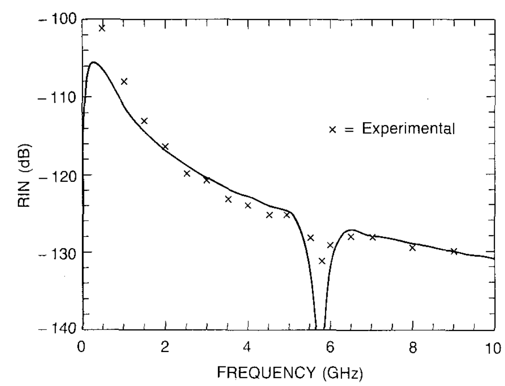


Fig. 4. Relative intensity noise: theory (for strongly multimode case) and experiment (data abstracted from Fig. 3).

and experimental curves. A minor discrepancy between the two curves is the lack of a second dip in the experimental RIN. This may be attributable to either the high receiver noise at the frequency of the expected second dip, or to the fact that total intensity is not so well stabilized as the frequency in question nears the relaxation oscillation frequency.

A more glaring discrepancy is that between the magnitudes of two curves; the theoretical curve peaks nearly 20 dB higher than the experimental curve. This clearly indicates that the model assumptions are not appropriate for the laser in question. In retrospect, this is not surprising: in DFB lasers different longitudinal modes can have very different field distributions inside the laser, and as a result different modes need not necessarily compete for the same gain. Thus partitioning effects can be much smaller than would be the case with a hypothetical Fabry–Perot (FP) laser with the same spectrum. The model used to derive (18) is a widely used model, and our results demonstrate that this model cannot be safely applied to DFB lasers.

A 1.55 μm multimode laser was used to test predictions for the multimode case. The optical spectrum and noise spectrum are shown in Fig. 3, for a modulation depth of 4.5% and bias current of 42 mA. Carrier power and noise power at 500 MHz were measured using the spectrum analyzer. These measurements yield and effective intensity noise of -101 dB (1 Hz) at 500 MHz. Fig. 4 shows the spectrum predicted by (21) for $M_{\text{eff}} = 6.7$ (calculated from the optical spectrum in conjunction with (26)), $1/\Delta\varepsilon = 5.75$ GHz, (compared to 5.2 GHz based on the nominal dispersion) and $1/(2\pi\tau) = 100$ MHz (chosen to fit the data). In the multimode case, theory and experiment agree relatively well.

Fig. 4 establishes a good correspondence between theory and experiment over a broad range of frequencies. For CATV applications, one would actually be interested in the quality of agreement over a much narrower range of frequencies (e.g., frequencies below 1 GHz). The experiments of this study do not directly address the adequacy of the models in this regime. In Fig. 4 there would appear to be a 4–5 dB discrepancy between theory and experiment at low frequencies; however there is considerable uncertainty in the model parameters and a different choice of parameters might provide good agreement in this regime.

A second observation to be made is that the theoretical models we have described nominally apply to unmodulated lasers, yet in most systems of practical interest the laser will

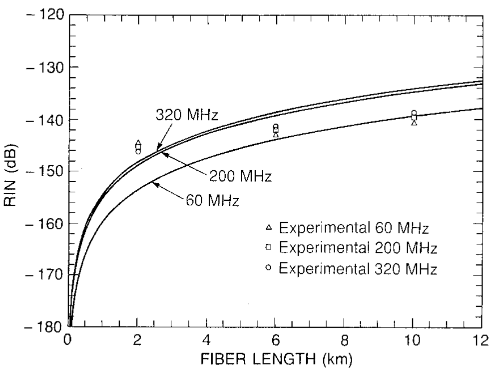


Fig. 5. Relative intensity noise: theory (strongly multimode result) versus fiber length.

be modulated. Empirically we have observed that applying CATV multichannel modulation does not significantly affect the observed noise spectrum. Thus the models we have described would appear to be relevant despite their failure to explicitly account for modulation effects.

A third experiment was conducted using a 1.3-μm multimode laser. The laser wavelength was 1.327 μm while the fiber dispersion zero was 1.307 μm. The level of LMPN was determined for three different carrier frequencies (60, 200, and 320 MHz) and for three different fiber lengths (2, 6, and 10 km). The noise present without any fiber was subtracted off. The results are plotted in Fig. 5. For comparison, theoretical results based on (21) have also been plotted, using the model parameters $1/(2\pi\tau) = 100$ MHz, $\Delta\varepsilon = (1.4 \text{ ps})$ (fiber length), and $M = 2$. (Note $M = 2$ was arrived at as a reasonable guess based on the observed spectrum; the calculated M_{eff} was somewhat larger.) One would not expect perfect agreement between theory and experiment, given that 1) the number of strong modes was bit low to justify calling the laser "strongly multimode"; and 2) near the dispersion minimum the dispersive delay between adjacent modes varies significantly as one moves across the laser spectrum. Even so, the theory appears to provide a useful estimate of observed noise levels. Note that this experiment indicates LMPN can be a concern even for systems using multimode lasers operating near the dispersion minimum.

Appendix A
Intensity-Noise Spectrum of Weak Side-Mode

Solving (13), one finds

$$\beta_{mm}(t+\Delta t) = \beta(t)e^{-\Delta t/2\tau_m} + \int_t^{t+\Delta t} e^{-(t+\Delta t-t')/2\tau_m} F_m(t')\,dt'. \tag{27}$$

Since $F_m(t)$ is taken to be Gaussian, it follows that $\beta_m(t)$ is also a Gaussian random process. Both $\beta_m(t)$ and $F_m(t)$ are taken to have zero mean, and for $\Delta t > 0$ and fixed t we can take $\overline{\beta_m^*(t)F_m(t+\Delta t)} = 0$. Thus,

$$\overline{\beta_m^*(t)\beta_m(t+\Delta t)} = \overline{|\beta(0)|^2}e^{-\Delta t/2\tau_m} = \overline{S}_m e^{-\Delta t/2\tau_m}, \quad \text{for } \Delta t > 0 \tag{28}$$

where $\beta_m(t)$ is taken to be normalized so that its magnitude squared is the optical power, $S_m(t)$. Since, the autocorrelation must map to its conjugate as $\Delta t \to -\Delta t$, it follows that in general the autocorrelation of the field is

$$\overline{\beta_m^*(t)\beta_m(t+\Delta t)} = \overline{S}_m e^{-|\Delta t|/2\tau_m}. \tag{29}$$

By the Gaussian moment theory [11], the autocorrelation of $S_m(t)$ can be expressed in terms of the autocorrelation of $\beta_m(t)$

$$\begin{aligned}\overline{S_m(t)S_m(t+\Delta t)} &= \overline{\beta_m^*(t)\beta_m(t)\beta_m^*(t+\Delta t)\beta_m(t+\Delta t)} \\ &= \overline{\beta_m^*(t)\beta_m(t)} \cdot \overline{\beta_m^*(t+\Delta t)\beta_m(t+\Delta t)} \\ &\quad + \overline{\beta_m^*(t)\beta_m(t+\Delta t)} \cdot \overline{\beta_m^*(t+\Delta t)\beta_m(t)} \\ &= \overline{S}_m^2 + \overline{S}_m^2 e^{-|\Delta t|/\tau_m}.\end{aligned} \tag{30}$$

Hence,

$$Cov[S_m(t), S_m(t+\Delta t)] = \overline{S}_m^2 e^{-|\Delta t|/\tau_m}. \tag{31}$$

Fourier transforming this, and taking into account the independence of side modes, one obtains (17).

References

[1] A. F. Judy, "Intensity noise from fiber Raleigh backscatter and mechanical splices," in *Proc. 15th European Conf. Opt. Commun. (ECOC '89)* (Gothenburg, Sweden), Sept. 1989.

[2] M. M. Choy, J. L. Gimlett, R. Welter, L. G. Kazovsky, and N. K. Cheung, "Interferometric conversion of laser phase noise to intensity by single-mode fiber-optic components," *Electron. Lett.*, vol. 23, no. 21, pp. 1151–1152, Oct. 1987.

[3] J. L. Gimlett and N. K. Cheung, "Effects of phase-to-intensity noise conversion by multiple reflections on gigabit-per-second DFB laser transmission systems," *J. Lightwave Technol.*, vol. 7, pp. 888–895, June 1989.

[4] T. E. Darcie, G. E. Bodeep, and A. A. M. Saleh, "Fiber-reflection-induced impairments in lightwave AM-VSB CATV systems," *J. Lightwave Technol.*, vol. 9, pp. 991–995, Aug. 1991.

[5] G. Grosskopf, L. Kuller and E. Patzak, "Laser mode partition noise in optical wideband transmission link," *Electron. Lett.*, vol. 18, no. 12, pp. 493–494, June 1982.

[6] A. Papoulis, *Probability, Random Variables, and Stochastic Processes.* New York: McGraw-Hill, 1965.

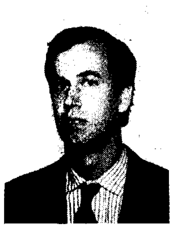
[7] C. H. Henry, P. S. Henry, and M. Lax, "Partition fluctuations in nearly single-longitudinal-mode lasers," *J. Lightwave Technol.*, vol. LT-2, pp. 209–216, 1984.

[8] P.-L. Lin, "Power fluctuations in the side modes of injection lasers," *J. Lightwave Technol.*, vol. LT-3, pp. 205–208, Feb. 1985.

[9] R. A. Linke *et al.*,"Mode power partition events in nearly single-frequency lasers," *J. Lightwave Technol.*, vol. LT-3, pp. 706–712, June 1985.

[10] R. H. Wentworth, "Noise of strongly-multimode laser diodes used in interferometric systems," *IEEE J. Quantum Electron.*, vol. 26, pp. 426–442, Mar. 1990.

[11] J. W. Goodman, *Statistical Optics.* New York: Wiley, 1985.

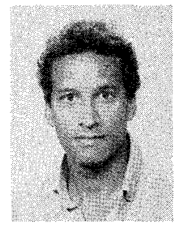


Robert H. Wentworth received the B.S. and B.A. degrees in physics and applied mathematics, respectively, from the University of Rochester, Rochester, NY, in 1980. Subsequently, he worked for two years as an electrical engineer for General Electric, participating in a number of aerospace projects. From 1982 to 1988 he studied at Stanford University, Stanford, CA, where he received the M.S. and Ph.D. degrees in applied physics. While at Stanford, he invesitgated coherence-multiplexed optical sensor arrays, communications systems involving optical amplifiers, mode partition noise and phase noise in semiconductor lasers, and the ultrafast optical Kerr effect in liquids.

He joined AT&T Bell Laboratories, Holmdel, NJ, in 1989. His recent research has emphasized the modeling of semiconductor lasers for use in lightwave cable television systems.

George E. Bodeep graduated from RCA Institute, New York, NY, in 1969 and received the B.S. degree (cum laude) from the New Jersey Institute of Technology, Newark, NJ, in 1980.

From 1969 to 1979 he was a Research Technician at RCA David Sarnoff Research Center, Princeton, NJ, where he worked on optical read-only memory, acoustical imaging for medical diagnosis and video disc. In 1979 he joined AT&T Bell Laboratories, Crawford Hill, Holmdel, NJ, where he has worked on optical fiber preform fabrication and characterization, spread spectrum radio for indoor wireless communication, and lightwave subcarrier multiplexing for CATV systems.



Thomas E. Darcie was born in Kitchener, Ontario, Canada, on April 1, 1956. He received the B.Sc. degree in physics from the University of Waterloo, Waterloo, Ontario, in 1977, and graduated from the University of Toronto Institute for Aerospace Studies where he received the M.A.Sc. degree in 1978 and the Ph.D. degree in 1982.

In 1982 he joined the technical staff of AT&T Bell Laboratories, Crawford Hill, Holmdel, NJ, where he studied gasdynamics and particle transport in optical fiber fabrication processes. Since 1984 he has investigated the nonlinear response characteristics of semiconductor lasers, the capabilities of lightwave systems that use subcarrier multiplexing, and the performance of resonant high-frequency receivers. His research on coherent lightwave techniques includes image-injection heterodyne receivers, polarization-diversity receivers, and nonlinear interactions in semiconductor optical amplifiers. Most recently, he has studied laser and system requirements for AM-VSB lightwave cable television systems. He is presently head of the Lightwave Communications Research Department at Crawford Hill.