Noise and Distortion Characteristics of Semiconductor Lasers in Optical Fiber Communication Systems

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(Invited Paper)

Abstract—The distortion and noise characteristics of semiconductor lasers in connection with optical fibers are reviewed. In particular, the intrinsic distortions and noise of semiconductor lasers together with the partition noise are discussed followed by a discussion on the influence of reflections. Modal noise phenomena due to the interference pattern at the endface of optical fibers are treated with respect to noise and distortions. Finally, the influence of polarization coupling in single-mode fibers on the resulting transmission behavior is discussed.

I. Introduction

WHEN CONSIDERING noise and distortions in optical fiber communication systems, the semiconductor laser emitter must be considered in addition to the receiver. It must be taken into account that noise and distortions of the semiconductor laser are altered considerably due to the interaction of the semiconductor laser with the optical fiber.

In this paper we will review the noise and distortion properties of semiconductor lasers in connection with the optical fiber with the main emphasis on optical fiber communication systems, even though the noise sources as discussed here are, for example, important also for optical fiber sensors.

We will first summarize the characteristics of semiconductor lasers in general, as far as these characteristics have some influence on distortion and noise behavior. The intrinsic distortions and noise are described in Section III. They arise if the semiconductor laser light is fed to a photodiode without an optical fiber. Regarding the interactions of the semiconductor laser with the optical fiber, the influence of partition noise will be discussed in Section IV, which is important if the fiber exhibits material dispersion or if the transmission loss is wavelength-dependent. An interaction with the active medium of the laser occurs if some light is reflected from the fiber back into the laser yielding, also, noise and distortions (Section V).

Forward transmission interferences may occur between different fiber modes (modal noise effects) yielding noise and distortions with respect to the transmitted optical power (Section VI). A discussion on the influence of polarization in single-mode fibers in Section VII will conclude the paper.

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II. Laser Characteristics in General

Stable transmission systems require semiconductor lasers which emit in a single transverse mode. Such lasers may be realized either as index-guided lasers or as gain-guided lasers according to Fig. 1. For index-guided lasers (type ⓐ in Fig. 1) a refractive index step is created parallel to the active layer by various technological means. For gain-guided lasers (type ⓑ), the waveguiding parallel to the junction is accomplished only by the lateral distribution of the carrier density which forms a gain profile by which the laser mode is guided [1].

In order to exhibit a stable transverse single-mode operation up to high light-output powers, the stripe widths of both laser types should be less than about 5 μm. Such narrow stripe lasers of both types do not exhibit "kinks" [2], [3], or self-pulsations [4] of their light-output, and only those lasers will be considered here.

Light-current characteristics of index- and gain-guided lasers are shown in Fig. 2, where the index-guided laser is represented by a CSP laser [5] and the gain-guided laser is a V-groove laser [6]. Both laser types exhibit a linear light-current characteristic above threshold. The transition behavior between the nonlasing and the lasing state, however, is different. The gain-guided V-groove laser exhibits a much smoother transition than the index-guided CSP laser. This difference in the transition behavior around threshold is closely related to the spectral characteristics as shown in Fig. 3. The left-hand side shows a typical spectrum of an index-guided laser exhibiting a nearly single-longitudinal mode emission, while the right-hand side shows the spectrum of a gain-guided V-groove laser. Both spectra have been measured at about 5 mW optical power. This difference in the spectral characteristics can be explained, at least partly, by the different amount of the spontaneous emission going into the oscillating laser modes [7] which strongly depends on the waveguiding inside the laser cavity. Because of the large spontaneous emission factor for a gain-guided laser one also obtains an intensive superradiance around threshold yielding the smooth transition between the lasing and the nonlasing state in Fig. 2.

For discussing noise and distortion properties, the coherence

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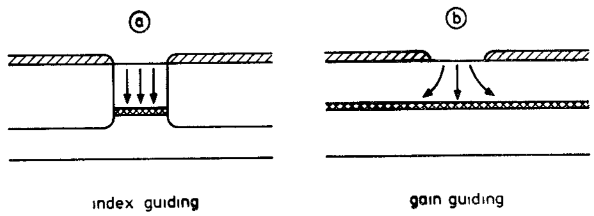

Fig. 1. Laser structures.

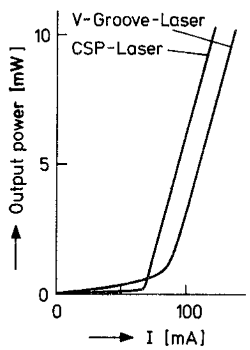

Fig. 2. Light-current characteristics of index- and gain-guided semiconductor lasers.

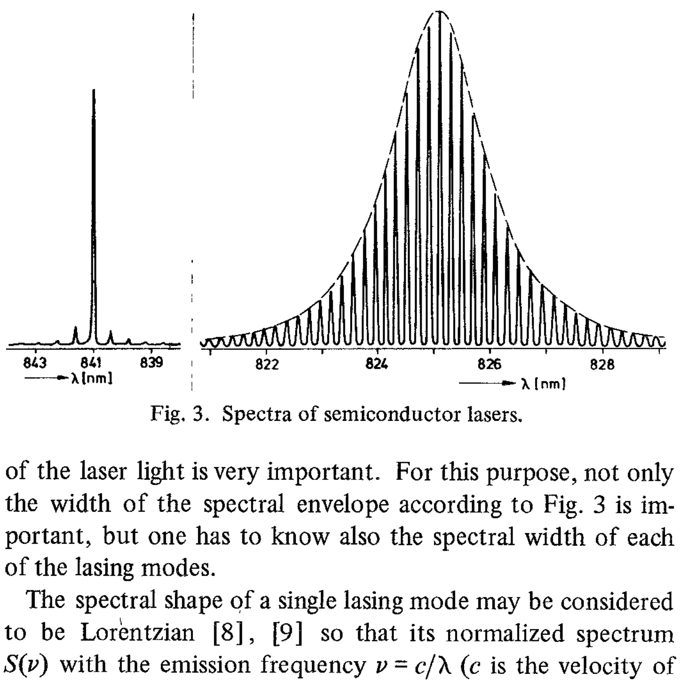

Fig. 3. Spectra of semiconductor lasers.

of the laser light is very important. For this purpose, not only the width of the spectral envelope according to Fig. 3 is important, but one has to know also the spectral width of each of the lasing modes.

The spectral shape of a single lasing mode may be considered to be Lorentzian [8], [9] so that its normalized spectrum $S(\nu)$ with the emission frequency $\nu = c/\lambda$ (c is the velocity of light, λ is the wavelength) may be written as

$$S(\nu) = \frac{2/(\pi\Delta\nu)}{1 + [2(\nu - \nu_c)/(\Delta\nu)]^2} \tag{1}$$

where ν_c is the center emission frequency and $\Delta\nu$ is the spectral width of the lasing mode. It is also convenient to introduce the coherence time τ_c

$$\tau_c = \frac{1}{2\pi\Delta\nu}. \tag{2}$$

The spectral width $\Delta\nu$ for index-guided single-mode lasers is usually in the order of several megahertz [8]-[10] corresponding to a coherence time in the order of 10-100 ns. Even spectral widths of several kilohertz have been reported [11] which may be obtained for special cases of optical feedback [8]. For a gain-guided laser, not only is the envelope of the spectrum much wider than for an index-guided laser, but the width of each lasing mode is also larger. Typically, coherence times $\tau_c \approx 30$-50 ps have been measured [12]-[14] for gain-guided lasers corresponding to a spectral width $\Delta\nu$ of several gigahertz. The lower limit for the spectral width of a single lasing mode is given by the amount of spontaneous emission going into the lasing mode [15] and therefore it is reasonable that a gain-guided laser with a large width of the envelope of the lasing spectrum also shows a broader spectrum of a single lasing mode. However, the spectral broadening cannot be explained solely by the spontaneous emission since any noise in the refractive index within the laser cavity, as introduced, for example, by noise of the carrier density within the active layer, may also yield a substantial line broadening [14].

III. Intrinsic Distortions and Noise of Semiconductor Lasers

Because of the good linearity above threshold of the light-current characteristics of state-of-the-art laser diodes according to Fig. 1, semiconductor lasers are well suited for direct analog modulation at least as long as they are operated without an optical fiber. Up to modulation frequencies of about 100 MHz the amount of distortions is mainly determined by the nonlinearity in the light-current characteristics, whereas for higher modulation frequencies nonlinear distortions due to relaxation oscillations occur [16]. Due to the smooth transition around threshold for a gain-guided laser there is also some curvature in the light-current characteristics above threshold. Because of this curvature, gain-guided lasers exhibit somewhat larger second-order harmonic distortions than index-guided lasers [17]. Both laser types, however, exhibit low third-order harmonic distortions. Fig. 4 shows the second- and third-order harmonic distortions a_{k2}, a_{k3} for a gain-guided V-groove laser at a modulation frequency $f = 30$ MHz versus the bias optical power with the modulation index m as a parameter [18]. If the laser is operated within one octave, second-order harmonic distortions are no longer important. For the third-order harmonic distortions, one obtains for a modulation index $m = 0.5$ a value of about -60 dB, which is comparable to index-guided BH lasers [19].

These intrinsic distortion figures are very satisfactory for analog transmission, but, in addition, the noise characteristics are to be considered.

The intrinsic noise of semiconductor lasers is governed by the quantum processes inside the laser cavity [20], [21]. These processes include the shot noise of the injection current, the spontaneous recombination of the carriers within the active layer, the light absorption and scattering, and the stimulated emission. The noise behavior may be described by use of the rate equation approach according to [20]-[22] as

$$\tau_{ph} \frac{dS_i}{dt} = -S_i [1 - g_i(N)] + \alpha_i N + \overline{F}_{pi}(t) \tag{3}$$

$$\tau_{sp} \frac{dN}{dt} = I/I_{\text{th}} - N - \sum_i g_i(N) S_i + \overline{F}_e(t) \tag{4}$$

with τ_{ph}, τ_{sp} denoting the photon lifetime and the lifetime of spontaneous emission, respectively. I and I_{th} denote the injection current and threshold current, respectively. N is the carrier density, normalized with respect to the carrier density

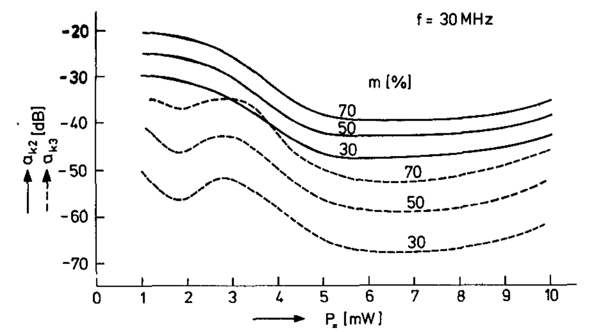

Fig. 4. Second (a_{k2})- and third (a_{k3})-order harmonic distortions for a V-groove laser.

above threshold. S_i, g_i, and α_i denote the normalized photon density, the normalized gain, and the amount of spontaneous emission, respectively, for the ith mode where the index i labels the different longitudinal lasing modes according to Fig. 3 with their respective emission wavelengths.

$\overline{F}_{pi}(t)$ and $\overline{F}_e(t)$ are the Langevin shot noise terms [20]-[22], accounting for the noise sources mentioned above.

The detected photon density at the receiver is a superposition of the photon densities of the different longitudinal lasing modes, so that the detected photon density S may be written as

$$S = \sum_i T_i S_i (t - t_i) \tag{5}$$

with T_i, t_i denoting the transmission coefficient and the delay for the ith lasing mode, respectively. If there is some wavelength filtering or material dispersion between laser and photodetector, T_i or t_i, respectively, will be different for different lasing modes.

To characterize the noise, one uses either the relative intensity noise (RIN)

$$\mathrm{RIN} = \frac{\langle |\Delta S(\omega)|^2 \rangle 2\Delta f}{S^2} \tag{6}$$

or the ratio between the dc-signal and the noise, which is just the inverse of the RIN

$$\frac{\text{dc-signal}}{\text{noise}} = \frac{S^2}{\langle |\Delta S(\omega)|^2 \rangle 2\Delta f} = \frac{1}{\mathrm{RIN}} \tag{7}$$

where $\langle |\Delta S(\omega)|^2 \rangle$ represents the noise power spectrum at the circular frequency ω, and Δf is the considered noise bandwidth. The ratios in (6) and (7) correspond to power ratios after the photodetector.

Fig. 5 shows measured intrinsic dc-signal/noise ratios at $f = 50$ MHz for an index-guided CSP-laser ⓐ and a gain-guided V-groove laser ⓑ if a photodiode is placed just in front of the laser so that T_i and t_i are constant. The signal/noise ratio has its minimum value (which corresponds to the noise maximum) a little bit above threshold and this minimum is much more pronounced for an index-guided laser than for a gain-guided laser. This behavior can also be calculated by use of (3) and (4) just taking into account the different coupling α_i of the spontaneous emission into the lasing modes [22]. For a laser length of 300-400 μm, a value of $\alpha_i \approx 10^{-5}$ is realistic for an index-guided laser [23], whereas $\alpha_i \approx 10^{-4}$ appears realistic for a gain-guided laser [7].

The noise maximum (minimum of signal/noise ratio) around threshold is also related to the smoothness of the light-current

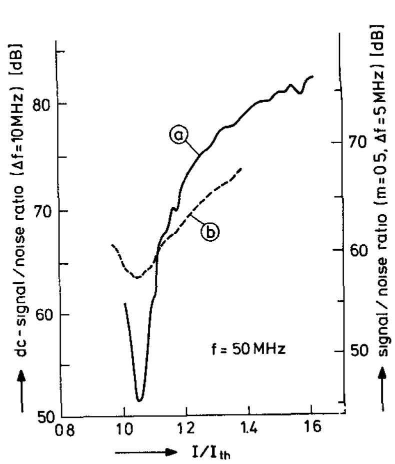

Fig. 5. Measured signal/noise ratios of semiconductor lasers with index-guiding ⓐ and with gain-guiding ⓑ.

characteristics around threshold. The smoother this transition is from the nonlasing to the lasing state the lower the noise maximum will be around threshold, yielding a lower noise maximum for a gain-guided laser than for an index-guided laser.

For injection currents sufficiently above threshold ($I/I_{th} > 1.2$) the index-guided laser in Fig. 5 exhibits a better signal/noise ratio than the gain-guided laser, but both lasers show dc-signal/noise ratios better than 70 dB for a noise bandwidth of $\Delta f = 10$ MHz ($\hat{=}$ RIN less than -140 dB for 1 Hz bandwidth) which is consistent also with other experimental results [24], [25].

The actual signal/noise ratios between the modulated signal and the noise are lower than the dc-signal/noise ratio, depending on the modulation index m of laser modulation. Therefore, the right-hand scale of Fig. 5 shows the extrapolated signal/noise ratio for $m = 0.5$ and a bandwidth of 5 MHz corresponding to the transmission of a single TV-channel yielding signal/noise ratios of 60-70 dB which are very satisfactory. However, if several channels are to be transmitted, a lower signal/noise ratio occurs.

The overall transmission quality depends on both the distortions and on the signal/noise ratio. According to distortions, the transmission quality is improved by decreasing the modulation index while a high signal/noise ratio requires also a high modulation index. Therefore, a compromise has to be met and a value of $m = 0.5$-0.7 is realistic [19], [26].

The above results for the intrinsic distortions and noise of a semiconductor laser hold only as long as the laser is operated without an optical fiber. Therefore, these figures set an upper limit for the achievable transmission quality.

IV. Partition Noise

In the preceding section the noise was discussed only for the case that all lasing modes are uniformly detected so that T_i and and t_i are constant. We will now discuss what happens if there is either a wavelength filtering ($\hat{=}$ varying T_i) or material dispersion (varying t_i) between laser and the receiving photodiode.

In that case, the partition noise has to be taken into account which means that the partition of different lasing modes within the total laser emission fluctuates [20]. Therefore, the spectrum at a time t_1 may look as shown in the left-hand side of Fig. 6, while at another time t_2 it may look different leaving the total output power mainly unchanged.

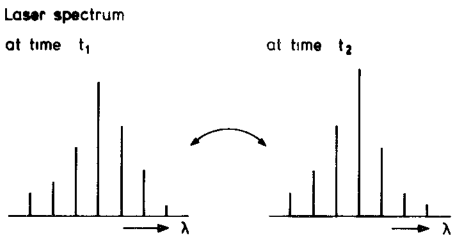

Fig. 6. Random spectra at different times illustrating the partition noise.

Thus, the individual modal photon densities S_i exhibit a very strong noise while the noise of the total photon density ΣS_i is relatively low.

The partition noise may be explained by (3) and (4). Due to the Langevin noise terms $\overline{F}_{pi}(t)$ and $\overline{F}_e(t)$, the carrier density N and the photon densities S_i will fluctuate around their stationary values. If, for example, the sum $\Sigma g_i(N) S_i$ is larger than its stationary value, the carrier density N will decrease because of (4), yielding also a decrease of the gain $g_i(N)$. Because of (3), the photon densities will then decrease as well, yielding a stabilization for the fluctuations of the sum $\Sigma g_i S_i$. Since the modal gains g_i are close to unity, this stabilization corresponds to a stabilization of the total photon density ΣS_i. This stabilization, however, does not work for any individual lasing mode, so that the noise for a single lasing mode is much larger than the noise of the total emission. According to experiments [27] this difference is in the order of about 30 dB.

The actual amount of partition noise strongly depends on the emission spectrum of the laser. If the laser would oscillate strictly in a single-longitudinal mode there is obviously no partition noise at all. On the other hand, considering a semiconductor laser emitting in a large number of longitudinal modes, one has a relatively large spontaneous emission factor α_i in (3) and the photon density S_i is relatively small since the total photon density is distributed among a large number of lasing modes. Therefore, one obtains a large relative amount of spontaneous emission (α_i/S_i) within the lasing modes. This large amount of spontaneous emission yields a stabilization of S_i in (3) and a damping of the fluctuations, yielding also a relatively low partition noise.

This behavior is sketched in Fig. 7, yielding a low partition noise for an almost single-mode laser. But even there, a considerable partition noise may occur between the lasing mode and the "so-called" nonlasing modes [28]. The worst situation occurs if the laser is oscillating in about three modes. Very high partition noise is obtained also if a single-longitudinal mode laser is in the unstable intermediate mode jumping situation of two lasing modes [14], as sketched in the lower part of Fig. 7.

The comparison in Fig. 7 is related to semiconductor lasers with equal cavity lengths. Some comments on the partition noise for lasers with different cavity lengths may be found in [22].

The foregoing discussion on the partition noise presumes a homogeneous gain saturation, so that the gain for each lasing mode i can be considered to be supplied by the same carrier

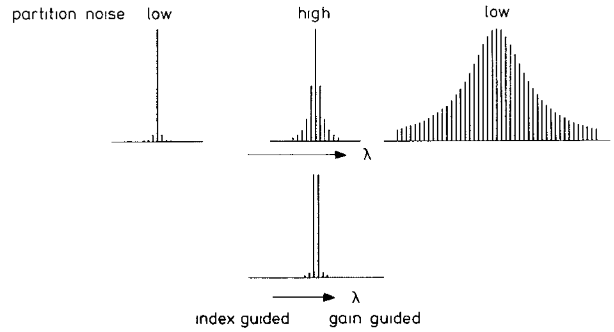

Fig. 7. Relation between the spectrum and the partition noise.

reservoir [denoted by N in (3) and (4)]. This homogeneous gain saturation has been observed in [29] but there also exists some indication for an inhomogeneous gain suppression [30]. If some inhomogeneous gain saturation occurs it is likely that the partition noise becomes lower since then each lasing mode i sees its own carrier reservoir yielding a more direct stabilization of the fluctuations of S_i.

As an example, the deterioration of the signal/noise ratio due to material dispersion, as introduced by the partition noise, will be studied. If the fiber between the laser and the receiving photodiode exhibits material dispersion different lasing modes i suffer different delays t_i. To combine the effects of T_i and t_i according to (5) one may introduce a complex transmission coefficient

$$\overline{T}_i = T_i \exp(j\omega t_i) \tag{8}$$

where ω is the circular frequency at which the noise is to be determined. The signal/noise ratio depends on the uniformity of the transmission for different modes i, which may be expressed by the differences

$$\Delta\overline{T}_{ij} = \overline{T}_i - \overline{T}_j \tag{9}$$

between different modes i and j. The larger $\Delta\overline{T}_{ij}$, the larger is the nonuniformity of the transmission so that the noise portions of the different lasing modes can no more effectively compensate at the receiver. If the noise at the receiver is mainly due to the partition noise, the noise amplitude $\Delta S(\omega)$ will be proportional to the nonuniformity $\Delta\overline{T}_{ij}$, so that the noise power and thus the relative intensity noise are proportional to $(\Delta\overline{T}_{ij})^2$.

As an example, the noise has been calculated by use of (3) and (4), taking the material dispersion of a 4 km length of fiber at a wavelength of 0.85 μm into account [22], yielding for $f = \omega/2\pi = 100$ MHz and for a wavelength spacing between adjacent modes $\Delta\lambda = 2$ Å a transmission difference

$$|\Delta\overline{T}_{i,i+1}| = |\overline{T}_i| \cdot 2\pi f \cdot |t_i - t_{i+1}| = |\overline{T}_i| \cdot 0.04. \tag{10}$$

The results are shown in Figs. 8 and 9, and [22]. Fig. 8 shows the calculated light–current characteristics and spectra where $\alpha_i = 10^{-5}$ has been assumed for the index-guided laser ⓐ and $\alpha_i = 10^{-4}$ for the gain guided laser ⓑ.

The calculated dc-signal/noise ratios for a noise bandwidth $\Delta f = 10$ MHz for both laser types are shown in Fig. 9 where the solid curves denote the intrinsic noise without material dispersion and the dashed curves take the material dispersion

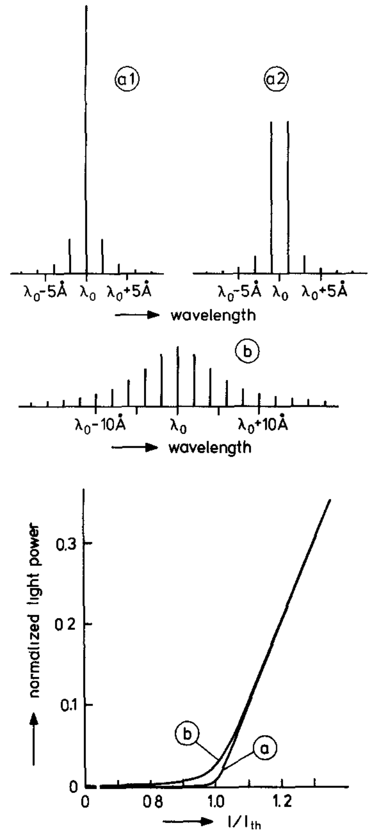

Fig. 8. Calculated light current characteristics and spectra for a gain-guided laser (b) and an index-guided laser (a).

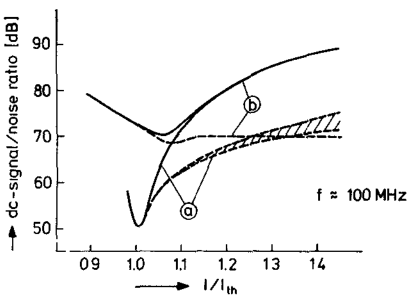

Fig. 9. Calculated dc-signal/noise ratio at $f = 100$ MHz. —— without material dispersion. – – – with material dispersion. The hatched area accounts for different spectra of the single-mode laser which are in between (a1) and (a2) in Fig. 8.

into account. The assumed nonuniformity of about 4 percent according to (10) already yields a substantial deterioration in the signal/noise ratio. Since the noise power is proportional to the square of the nonuniformity, doubling of the material dispersion or of the fiber length, respectively, would yield a further 6 dB decrease of the signal/noise ratio.

These problems are mostly avoided if the fiber is operated near the dispersion free wavelength around 1.3 μm [31], but for still larger wavelengths in the 1.5-1.6 μm wavelength range considerable material dispersion occurs. In this wavelength range, fiber lengths in the order of 50 km become feasible [32] and over this length delay differences between adjacent modes of 500-1000 ps may occur giving rise to a signal/noise ratio which is 20 dB worse than given in Fig. 9.

For the single-mode laser model (a) in Fig. 8, a relatively large power portion is contained in the nonlasing modes. In an actual index-guided laser, the nonlasing modes are usually more strongly suppressed as demonstrated in Fig. 3. Therefore, actual index-guided lasers show very little partition noise [14], [33], at least as long as the unstable mode jumping situation of two lasing modes is avoided by a careful wavelength control.

The considerations from above are restricted to CW-operated laser diodes. If a single-mode laser is modulated, it eventually may become multimode and then dynamic partition noise effects occur [34].

We have thus shown that partition noise may indeed set a strong limitation for the achievable signal/noise ratio. This deterioration of the signal/noise ratio can only be avoided if a wavelength near the dispersion minimum is used.

V. Noise and Distortions Due to Reflections

Reflection problems are illustrated in Fig. 10. If the laser light is launched into a fiber, some light portion will be reflected back to the laser due to some discontinuity or due to a fiber connector.

Because of the external reflection, two cavities (the laser cavity and the external cavity) are formed and the interaction between these two cavities has to be considered. The mode spacing $\Delta\lambda$ between adjacent cavity modes is given as

$$\Delta\lambda = \frac{\lambda^2}{c \cdot \tau} \tag{11}$$

where τ is the roundtrip time of the cavity. For a laser cavity of 400 μm length, the roundtrip time is in the order of 10-15 ps while the roundtrip time of the external cavity is generally much larger. Therefore, the spacing between the laser cavity modes is usually much wider than the spacing of the external cavity modes.

The interaction between these two cavities may change the emission spectra considerably [35], [36]. One has to distinguish between near-end reflections occurring up to several centimeters from the laser and far-end reflections which may occur several kilometers away from the laser.

A. Near-End Reflection

For the near-end reflection an index-guided laser emitting in a single-longitudinal mode is considered. This single lasing mode will be stabilized if the wavelength of the respective laser cavity mode coincides with an external cavity mode. In this situation the linewidth of the mode may be considerably narrowed [8], [37] yielding spectral widths in the order of 100 kHz instead of several megahertz. If, however, the length of one of the cavities is slightly shifting, the lasing mode may shift considerably to another wavelength where coincidence between the resonances of the two cavities is achieved again. A change of the external cavity length by $\lambda/2$ may yield a change of the emission wavelength of 8 nm [38]. In connection with material dispersion this large wavelength change yields a considerable change of the delay through the fiber which may not be acceptable.

The emitted light intensity depends on whether the reflected light interferes constructively or destructively with the laser

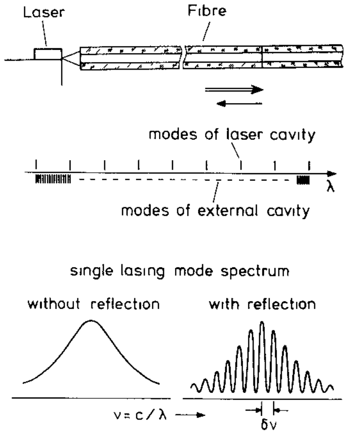

Fig. 10. Semiconductor laser with reflections.

light. Therefore, the emitted light intensity fluctuates if the external cavity length is changed [39]. A similar effect occurs if the injection current is changed, since any change of the injection current also yields a change of the laser temperature which leads to a shift of the laser cavity modes [40]. Therefore, when plotting the light intensity against the injection current, a nonlinear characteristic is observed [41], yielding increased higher order harmonic distortions.

Due to the near-end reflections, a low-frequency noise occurs [42] which is due to fluctuations of the length of either the laser cavity or the external cavity. The power spectrum of these fluctuations extends up to several kilohertz [42].

The foregoing discussion on the influence of near-end reflections was devoted mainly to single-longitudinal-mode lasers. For a multimode gain-guided laser, spectral changes due to reflections are also observed [43] but the interactions of the different lasing modes with the external cavity tend to be averaged out, so that the overall effect is not so severe as for an index-guided laser.

B. Far-End Reflections

Due to the near-end reflections, noise occurs mainly at low frequencies. If, however, the inverse roundtrip time of the external resonator comes into the order of the relaxation resonance frequency pulsations of the light-output and noise may occur also at high frequencies. This condition is met for a length of the external resonator of about 10 cm. If the external resonator is longer, one is in the region of the far-end reflections; and we will study especially the case in which the roundtrip time of the external resonator τ_{ext} is larger than the coherence time τ_c according to (2) of the semiconductor laser.

For this situation the lower part of Fig. 10 shows the spectrum of a single lasing mode without and with reflection. Without reflection one obtains a Lorentzian line according to (1), and this spectrum interacts with the external cavity in the case of reflections. Instead of the single lasing mode one then obtains submodes corresponding to the external cavity modes, which are spaced by $\delta\nu = 1/\tau_{ext}$ [44]. A single lasing mode thus changes to a number of submodes, which are very narrowly spaced. If, for example, the reflection occurs at a fiber length 1 km away from the laser, the submodes are spaced by $\delta\nu = 100$ kHz, and if these submodes are sufficiently strong, they may mode-lock, yielding pulsations or noise of the light intensity at 100 kHz and its higher harmonics up to the relaxation resonance frequency [44], [45]. Due to this self-modulation the spectral envelope of the submodes will also be broadened [44].

The amount of reflections which can be tolerated depends critically on the degree of coherence of the emitted laser light. In general, a laser will be the more sensitive to reflections the more coherent it is.

It is obvious that for the near-end reflection, the reflection coefficient with respect to the amplitude of the optical field must be considered [42] which corresponds to the square-root of the intensity reflection coefficient R_I. But even for the far-end reflection, the reflection coefficient with respect to amplitude must be considered since the coherence time of each of the submodes is larger than the external roundtrip time so that the reflection is still coherent.

As a rule of thumb, the reflection will affect the laser emission if the reflection coefficient with respect to amplitude is larger than the relative amount of spontaneous emission within the lasing modes yielding critical limits for the reflection coefficients with respect to amplitude of about 10^{-4} for an index-guided laser and about $3 \cdot 10^{-3}$ for a gain-guided laser. These reflections are sufficient to change the spectrum of a single lasing mode from the left-hand side in Fig. 10 to the right-hand side [46], but it is difficult to estimate what amount of reflections is really required to introduce self-pulsations and excess noise.

Actually, one is interested in the reflection coefficients with respect to intensity R_I which should follow

$$R_I < 10^{-8}\text{-}10^{-6} \quad \text{for single-longitudinal mode lasers}$$

$$R_I < 10^{-5}\text{-}10^{-3} \quad \text{for multilongitudinal mode lasers} \tag{12}$$

for low noise transmission. The smaller figures 10^{-8}, 10^{-5} are the squared amplitude reflection coefficients from above, and the spread of two orders of magnitude is introduced because of the uncertainty at what reflection level pulsations and noise really occur. It should be noted, however, that there is a gradual increase in noise for increasing reflection [42], [47].

The reflection coefficient which actually occurs in an optical fiber communication system may be estimated as

$$R_I = \eta^2 \cdot \exp(-2\alpha L)\, R/M \tag{13}$$

where η is the coupling efficiency between laser and fiber, α the fiber attenuation, L the fiber length between laser and the reflection point with the reflection coefficient R, and M the number of modes propagating in the fiber. Equation (13) can be easily explained by assuming a truly single-mode fiber with $M = 1$. The coupling efficiency η is then equal for coupling light from the laser into the fiber and back because of reciprocity. The light is traveling forth and back along the fiber yielding a transmission efficiency of $\exp(-2\alpha L)$ and finally the reflection coefficient R at the reflection point has to be accounted for. If M modes are guided by the fiber, the reflected light power is distributed among these M modes and therefore, on the average, only $1/M$th part is coupled back. The actual amount of reflection, however, may fluctuate around this average value since it depends on the state of polarization and on the speckle pattern of the returning light.

For typical parameters ($\eta = 0.5$, $\alpha L = 1.5$ dB, $R = 0.04$) one obtains a reflection coefficient $R_I \approx 2 \cdot 10^{-3}$ for a single-mode fiber ($M = 2$ because of two polarizations) and $R_I \approx 10^{-5}$ for a multimode fiber (assuming $M = 400$). Therefore, the use of a single-mode fiber is much more critical with respect to reflections than the use of a multimode fiber [47].

For a low-noise optical fiber transmission system, an optical isolator is required for single-longitudinal-mode lasers in connection with multimode, as well as with single-mode, fibers. On the other hand, if a multilongitudinal-mode laser is used in connection with a multimode fiber an optical isolator may be omitted.

Noise spectra for gain- and index-guided lasers with and without reflections under the same conditions are shown in Fig. 11 with an injection current slightly above threshold ($I/I_{th} = 1.04$). For the gain-guided laser (V-groove laser) the noise spectra with and without reflections are nearly identical, whereas the index-guided laser exhibits noise maxima at multiples of 500 MHz with reflections, corresponding to the inverse roundtrip time of the external resonator with a length of about 30 cm.

The problems of the excess noise due to reflections are most severe for analog systems, but also for digital transmission reflections may yield a reduction of the achievable bit error rate [48], [49].

VI. Modal Noise Phenomena

If the light of the laser is launched into a multimode fiber, the excited modes may interfere with one another yielding a speckle pattern at the fiber endface [50], [51]. This speckle pattern is very sensitive with respect to external forces, temperature change, etc., acting upon the fiber, especially as it is very sensitive to even a minute change of the emission wavelength [52].

If the fiber is followed by an imperfect fiber connector as shown in Fig. 12, any change of the speckle pattern also yields a change of the coupling efficiency [50], [52]. If considering a monochromatic light source with an emission frequency $\nu = c/\lambda$, the coupling efficiency η at the fiber connector between fibers I and II is obtained as [53]

$$\eta = \frac{1}{P_{\mathrm{I}}} \sum_{\nu=1}^{N} \sum_{\kappa=1}^{N} \sqrt{P_\nu P_\kappa} \cos(\varphi_{\nu\kappa} - 2\pi\tau_{\nu\kappa}(\nu - \nu_0)) F_{\nu\kappa} \quad (14)$$

with

$$F_{\nu\kappa} = \sum_{\mu=1}^{M} \mathrm{I}_{\nu\mu} \mathrm{I}_{\kappa\mu} \quad (15)$$

and P_ν, P_κ, and P_{I} denoting the power in mode ν, κ and the total power, respectively, in fiber I. N and M denote the number of propagating modes in fibers I and II, respectively. $\mathrm{I}_{\nu\mu}$ is the power coupling coefficient from mode ν in fiber I to mode μ in fiber II. ν_0 is an arbitrary emission frequency, at which $\varphi_{\nu\kappa}$ denotes the phase difference between the modes ν, κ. $\tau_{\nu\kappa}$ is the delay difference between the modes ν, κ through fiber I.

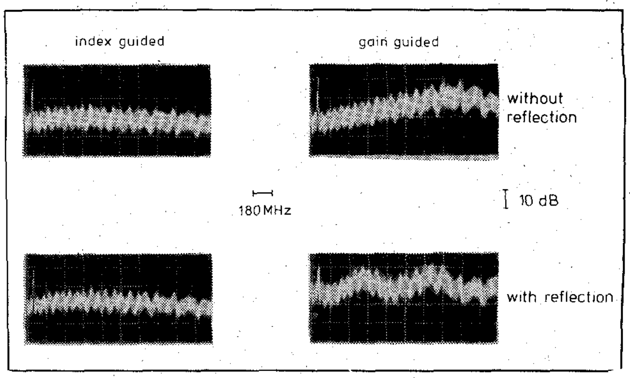

Fig. 11. Noise spectra for semiconductor lasers with index- and gain-guiding with and without reflections. $I/I_{th} = 1.04$.

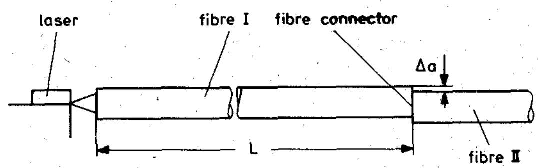

Fig. 12. Fiber connector with preceding fiber.

$F_{\nu\nu}$ gives the coupling efficiency with which the mode ν is coupled to fiber II and $F_{\nu\kappa}$ with $\nu \neq \kappa$ denotes an interference coefficient between the modes ν, κ which determines the magnitude of modal noise. In order to reduce modal noise one may try to reduce $F_{\nu\kappa}$ with $\nu \neq \kappa$ by a special connector design [54]. The proposal in [54], however, yields a modal noise reduction only under special assumptions [55].

Fig. 13 shows a calculated $\eta(\nu)$-characteristic which has been obtained by evaluating (14) for identical near-square-law fibers [52] with a fiber parameter $V = 21$ ($V = (2\pi a/\lambda)\ n_0\sqrt{2\Delta}$ where a is the core radius, λ is the wavelength, n_0 is the refractive index of fiber core, and Δ is the relative refractive index difference between core and cladding). For simplicity, only one polarization is considered. The dashed and solid curves are obtained when starting from different speckle patterns at $\nu = \nu_0$ ($\triangleq$ choice of $\varphi_{\nu\kappa}$).

The mean coupling efficiency is about 0.8 ($\triangleq$ transmission loss of about 1 dB) but it fluctuates considerably where the difference in emission frequency between the minimum and the maximum corresponds to only about $\delta\nu = 1/\tau_{\mathrm{rms}}$, with τ_{rms} denoting the root-mean-square pulse broadening of fiber I. Thus, a relative change in the emission frequency by about 10^{-5}-10^{-6} already suffices to change the coupling efficiency considerably.

For estimating the signal/noise ratio due to modal noise one is interested in the variance of the coupling efficiency [53]

$$\sigma(\eta) = \sqrt{\langle\eta^2\rangle - \langle\eta\rangle^2} = \frac{1}{P_{\mathrm{I}}} \sqrt{\sum_{\substack{\nu=1 \\ \nu\neq\kappa}}^{N} \sum_{\kappa=1}^{N} P_\nu P_\kappa (F_{\nu\kappa})^2} \quad (16)$$

with $\langle\ \rangle$ denoting averaging over all possible speckle patterns.

If the fluctuations of the coupling efficiency—as introduced either by external fluctuations (e.g., pressure, temperature) or by wavelength fluctuations—have spectral components

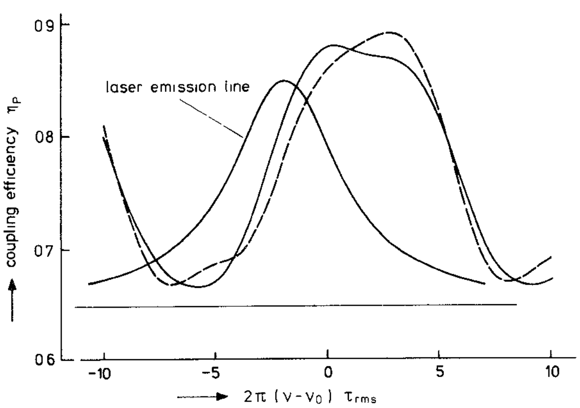

Fig. 13. Coupling efficiency at a fiber connector versus the emission frequency ν.

which are fully within the modulation band, one simply obtains for the dc-signal/noise ratio

$$\frac{\text{dc-signal}}{\text{noise}} = \left(\frac{\langle\eta\rangle}{\sigma(\eta)}\right)^2. \tag{17}$$

Fig. 14 shows the $\sigma(\eta)/\langle\eta\rangle$ as calculated from (16) for near-square-law fibers with different fiber parameters V. A typical multimode fiber with a core diameter of 50 μm corresponds to $V = 21$ and 31 for a wavelength of about 1.3 μm and 0.85 μm, respectively. The lower the coupling loss the lower also is the variance of the coupling efficiency and thus the noise, where, for example, a dc-signal/noise ratio of 20 dB corresponds to $\sigma(\eta)/\langle\eta\rangle = 0.1$. This signal/noise ratio estimate from (17) is certainly a worst case estimate.

The calculation of $\sigma(\eta)$ according to (16) involves the summation of a large number of terms. If, for example, the fiber I carries 200 modes, the summation involves 40 000 terms. Some of these terms vanish, but in any case the calculation is possible only numerically and takes considerable computation time.

By using speckle theory one arrives at a relatively simple expression [56]-[59]

$$\sigma(\eta)/\langle\eta\rangle \approx \sqrt{\frac{1-\langle\eta\rangle}{N\langle\eta\rangle}} \tag{18}$$

which holds as long as the number N of modes guided by fiber I is large. Equation (18) is in good agreement with the numerically evaluated result in Fig. 14 for large coupling losses in excess of about 1 dB. For low coupling losses, however, (18) yields larger fluctuations of the coupling efficiency than the numerical evaluation of (16).

To simplify the analysis it is useful to approximate the generally complicated $\eta(\nu)$-curve according to Fig. 13 by a sinusoidal function [60] which is allowed as long as the coupling loss is low ($\langle\eta\rangle \gtrsim 0.8$)

$$\eta(\nu) \approx \langle\eta\rangle + \sqrt{2}\cdot\sigma(\eta)\cos(\varphi_0 + 2\pi\tau_{\text{eff}}\cdot(\nu-\nu_0)). \tag{19}$$

In this simplified form, the speckle pattern is represented by φ_0 and τ_{eff} is in the same order of magnitude as τ_{rms}, but in general it will be different. For Fig. 13, for example, we have approximately $\tau_{\text{eff}} = \tau_{\text{rms}}/2$.

Equation (19) corresponds to (14) for a two-mode fiber with $N = 2$ where only the factor in front of the cosine term has been adjusted so that (16) is satisfied. This two-mode model is very suitable to get a quick insight into more complex situations.

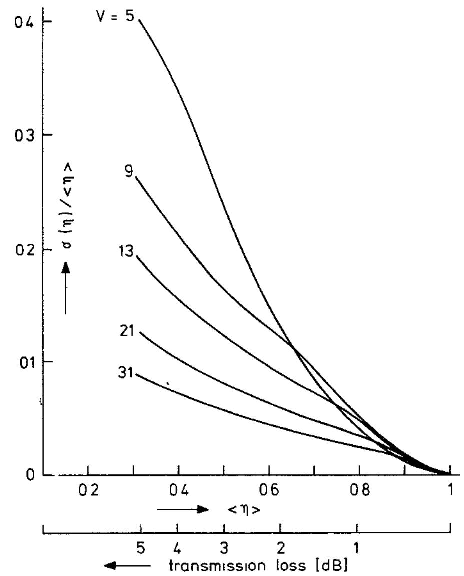

Fig. 14. Variance of coupling efficiency due to modal noise for different fiber parameters V.

The above considerations hold for a monochromatic signal only. If, however, a partially coherent light source with a Lorentzian-shaped spectrum according to (1) is considered (which is also shown in Fig. 13), the effective coupling efficiency η_s is obtained as a weighted average over the $\eta(\nu)$-curve

$$\eta_s = \int S(\nu)\,\eta(\nu)\,d\nu. \tag{20}$$

By using (19), one gets a very simple solution

$$\eta_s \approx \langle\eta\rangle + \sqrt{2}\,\sigma(\eta)\exp(-\tau_{\text{eff}}/(2\tau_c)) \cdot\cos(\varphi_0 + 2\pi\tau_{\text{eff}}(\nu_c - \nu_0)) \tag{21}$$

where the fluctuation amplitude is reduced by a factor exp $(-\tau_{\text{eff}}/(2\tau_c)$. Actually, by a more accurate analysis [53], the relation between the fluctuation amplitude and τ_{rms} (which is proportional to τ_{eff}) is more complicated. Fig. 15 shows the variance of the effective coupling efficiency $\sigma(\eta_s)$ versus τ_{rms}/τ_c for near square-law fibers with a power-law profile with exponents of $\alpha = 2.05$ (solid curves), $\alpha = 2.3$ (dashed curves), and fiber parameters $V = 21$ and 31. For small τ_{rms}/τ_c an exponential decaying function appears to be a good approximation; for large τ_{rms}/τ_c, however, the decay is much slower. In that case, the approximation by a two-mode fiber according to (19) is no more appropriate since in a real multimode fiber there are a lot of modes with nearly equal delays which may interfere with one another even for relatively incoherent sources.

In any case, the lower the coherence time τ_c of the light source the lower the fluctuations of the coupling efficiency will be [50], [53], [59], [61]. If the laser emits in N_L lasing modes, the fluctuation amplitude of the coupling efficiency will be furthermore reduced by a factor of $\sqrt{N_L}$ [53],

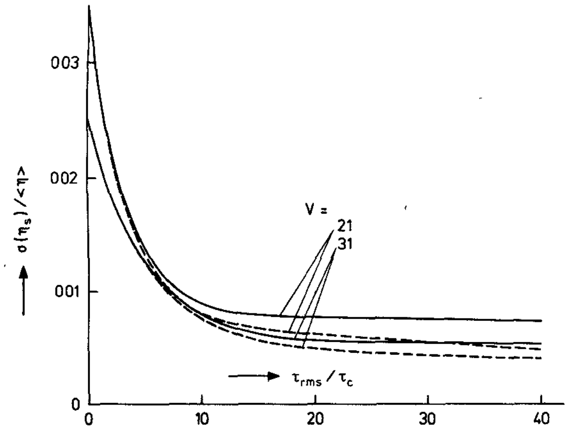

Fig. 15. Variance of coupling efficiency for partially coherent sources. Assumption: $\langle\eta\rangle = 0.8$.

[59] provided that the fluctuation of coupling efficiency for different lasing modes are independent from one another. Therefore, a gain-guided laser emitting in a large number of modes yields much lower fluctuations than an index-guided single-mode laser.

A. Partition and Phase Noise

So far we have mainly considered the variance of the coupling efficiency which, in the worst case, may yield the signal/noise ratio as given in (17). This noise is to a large extent due to external fluctuations which occur at low frequencies. We will now consider to what extent the intrinsic laser fluctuations will affect the signal/noise-ratio at higher frequencies if a fiber connector is present.

Since the coupling efficiency depends on the emission frequency or emission wavelength, the partition noise becomes important. For $\langle\eta\rangle = 0.5$ and $\sigma(\eta) = \langle\eta\rangle/\sqrt{2}$ the approximate equation (19) corresponds to the transmission characteristics of a Michelson interferometer with τ_{eff} denoting the delay difference between the two interferometer arms. The noise after such an interferometer can easily be measured [10], [14], [62]. If this noise is mainly due either to partition noise or due to phase noise one may easily obtain their noise portion at the fiber connecter as

$$\text{RIN} = \frac{2\sigma^2}{\langle\eta\rangle^2}\ \text{RIN}|_{\text{Michelson}} \tag{22}$$

since this noise portion is proportional to the square of the nonuniformity of the transmission (corresponding to σ^2) as explained in Section III.

The influence of partition noise in a Michelson-interferometer has been measured in [14] for a typical multilongitudinal-mode laser as $\text{RIN}|_{\text{Michelson}} \approx -110$ dB for 1 Hz bandwidth, yielding, for example, a RIN due to a fiber connector with $\sigma(\eta)/\langle\eta\rangle = 0.05$ as RIN = -133 dB for a noise bandwidth $\Delta f =$ 1 Hz which is not very far from the intrinsic laser noise. The phase noise portion is of a similar order of magnitude [10], [14], [62] unless very low frequencies down to some kilohertz are considered [62].

To understand the influence of phase noise we will consider Fig. 13 where a laser emission line is shown in the $\eta(\nu)$-diagram. The spectral broadening of the laser emission line means that the actual laser emission frequency fluctuates and these fluctuations of the emission frequency are transferred to fluctuations of the coupling efficiency of the fiber connector. This frequency- or phase-noise portion cannot be simply studied by only considering the spectral shape according to (1). Actually, the phase fluctuations of the laser light have to be considered more in detail.

We may write for the complex optical field $E(t)$

$$E(t) = E_0 \exp\left(j2\pi\nu_c t + \varphi(t)\right) \tag{23}$$

with the center emission frequency ν_c and the random phase $\varphi(t)$. It is reasonable to assume a random walk for the phase as

$$\langle(\varphi(t+\tau) - \varphi(t))^2\rangle = |\tau|/\tau_c \tag{24}$$

and also a Gaussian probability density function for the phase change [63]. By making these assumptions one also gets the Lorentzian shaped spectrum according to (1) [64]. By using (24) together with a Gaussian probability distribution, the statistics for $\varphi(t)$ are completely determined and the RIN in a Michelson interferometer may be obtained [10], [14], [63], yielding finally with (22) for the RIN due to a fiber connector

$$\text{RIN} = \frac{\sigma^2(\eta)}{\langle\eta\rangle^2}\cdot 4\Delta f\cdot\tau_c\cdot f(\tau_{\text{eff}}/\tau_c) \tag{25}$$

with

$$f(\tau_{\text{eff}}/\tau_c) = 1 - \exp\left(-|\tau_{\text{eff}}/\tau_c|\right)\left(1 + |\tau_{\text{eff}}/\tau_c|\right). \tag{26}$$

The noise in (25) corresponds to an averaged noise, averaged over all possible speckle patterns. Equation (25) holds for noise frequencies below the cutoff frequency which is given by $1/(2\pi\tau_{\text{eff}})$ for $\tau_{\text{eff}} \ll \tau_c$ and by $1/(2\pi\tau_c)$ for $\tau_{\text{eff}} \gg \tau_c$ [10], [63]. At very low frequencies of up to several kilohertz the noise may be much larger [62] than in (25) but these extremely low frequencies will not be considered here.

The phase noise portion according to (25) will neither be critical for very large τ_c [yielding small $f(\tau_{\text{eff}}/\tau_c)$] nor for very low τ_c. For intermediate values of τ_c, however, the noise may become quite large. When assuming $\tau_c = \tau_{\text{eff}} = 1$ ns one obtains with $\sigma(\eta)/\langle\eta\rangle = 0.05$ a relative intensity noise of RIN = -116 dB which is by orders of magnitude worse than the intrinsic laser noise as given in Section III.

B. Nonlinear Distortions

Nonlinear distortions occur due to a fiber connector, since the direct modulation of a semiconductor laser not only yields a modulation of the optical power but also of the emission wavelength [13], [65]. The modulation of the center emission frequency may be written as

$$\nu_c(t) = \nu_{c0} + (\Omega_m/2\pi)\cos(2\pi f_m t) \tag{27}$$

with the modulation frequency f_m and the modulation amplitude Ω_m of the emission frequency. Due to the modulation of the emission wavelength, the coupling efficiency will also be modulated, and inserting (27) into (21), for example, yields high-order harmonics for $\eta_s(t)$ and these harmonics are expressed by Bessel functions [66]. The magnitude of the higher order harmonic distortions depends on the amplitude Ω_m of the frequency modulation and especially for modulation frequencies $f_m < 1/2\pi\tau_{\mathrm{Th}}$—where τ_{Th} is the thermal time constant of the laser—the wavelength modulation is very large [13], yielding harmonic distortions up to the 70th order if the laser is modulated with a modulation frequency f_m = 10 kHz [66]. For larger modulation frequencies in excess of about 10 MHz, Ω_m is much smaller with typical values of $\Omega_m/2\pi = 5$–10 GHz for a gain-guided multilongitudinal-mode laser [13] and about $\Omega_m/2\pi \approx 1$ GHz for a single-longitudinal-mode laser [65].

The actual second- and third-order harmonic distortions, which are to be expected due to a fiber connector, are shown in Fig. 16 [67], showing the mean second-order [Fig. 16(a)] and third-order [Fig. 16(b)] harmonic distortions for a fiber connector with $\langle\eta\rangle = 0.8$ and a fiber parameter $V = 31$. The left-hand scales in Fig. 16 hold for a single-longitudinal-mode laser whereas the right-hand scales hold for a multilongitudinal-mode laser emitting in 10 lasing modes.

If a single-longitudinal-mode laser is used with a fiber with $\tau_{\mathrm{rms}} = 1$ ns (so that $\tau_{\mathrm{rms}}/\tau_c \approx 0$) one obtains second- and third-order harmonic distortions of -38 dB and -43 dB, respectively, while the use of a gain-guided multilongitudinal-mode laser with its low coherence time yields second- and third-order harmonic distortions of at most -50 to -60 dB.

These distortion figures indicate that an index-guided single-mode laser can in general no more be used for high-quality analog transmission in connection with multimode fibers, whereas the distortion figures for a gain-guided multilongitudinal-mode laser are acceptable for many applications.

VII. Polarization Problems in Single-Mode Fiber Transmission

In order to avoid these modal-noise related phenomena it is useful to use single-mode fibers as the transmission medium. But even there, distortions and noise may occur. Nonlinear distortions, for example, are obtained just due to material dispersion [68]-[71] since the spectral components which are created during the modulation suffer different delays through the fiber. These distortions, however, occur only for modulation frequencies beyond the gigahertz range and they become very small if the emission wavelength of the laser is set near the minimum of material dispersion.

In addition, it has to be taken into account that, strictly speaking, a single-mode fiber is a two-mode fiber because of its two guided polarizations. If the fiber exhibits some polarization dispersion [72] the state of polarization within the fiber becomes wavelength-dependent and any element with polarization sensitive loss then produces a coupling-efficiency versus wavelength curve similar to Fig. 13 yielding all phenomena as discussed in the previous section. Even though there is a theory on polarization sensitive loss of a single-mode fiber connector [73], the paraxial nature of the wave propagation in a single-mode fiber makes it unlikely that usual kinds of perturbations acting upon the fiber or state-of-the-art fiber connectors produce any substantial polarization dependency.

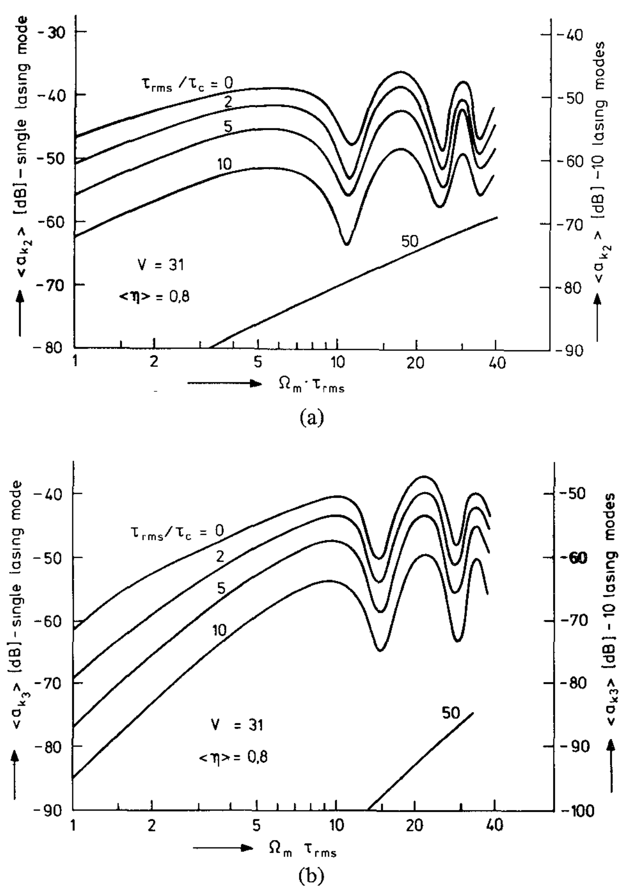

Fig. 16. (a) Second-order and (b) third-order harmonic distortions with the ratio between the pulse broadening of the fiber τ_{rms} and the coherence time τ_c as a parameter. Assumptions: $V = 31$, $\langle\eta\rangle = 0.8$.

Therefore, it is likely that an actual well-designed single-mode fiber transmission line does not exhibit any polarization-dependent loss. But even there, nonlinear distortions and excess noise may occur. If the fiber line shows some polarization coupling—which is likely for any fiber with low birefringence—the actual amount of coupling will depend on the actual state of polarization at the coupling point. The problem of polarization coupling may be explained by use of the single-mode fiber transmission line model according to Fig. 17 [74], [75] consisting of two jointed linearly birefringent fibers with the main polarization axes exhibiting an angle α with respect to one another at the joint. In this model the polarization coupling is concentrated at the joint. If the light source excites both polarizations of fiber I the polarization at the joint will be wavelength-dependent. The relative mode excitation of the two modes in fiber II will also depend on the state of polarization at the joint and will thus depend on the wavelength. Depending on the ratio with which the fast and slow mode of fiber II are excited, the effective delay through the fiber line is changed. Therefore, the effective delay through the fiber depends on the emission wavelength as sketched in Fig. 18. The laser modulation with its wavelength modulation then yields a modulation of the delay through the fiber and this delay modulation yields nonlinear distortions which increase with increasing modulation frequency [74].

If we tolerate an upper limit for the second-order harmonic

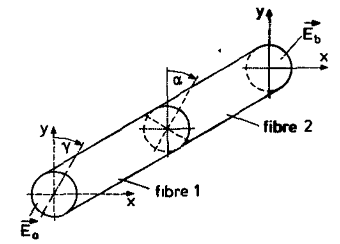

Fig. 17. Single-mode fiber transmission line model.

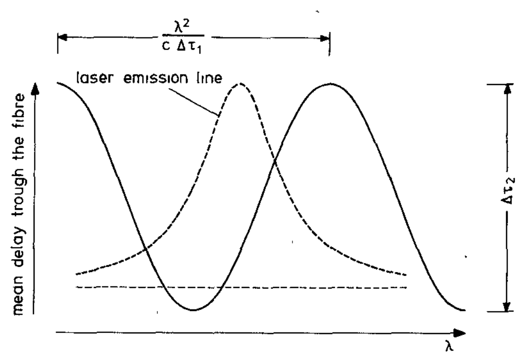

Fig. 18. Mean delay through the single-mode fiber transmission line according to Fig. 17 as a function of wavelength. $\Delta\tau_1$ and $\Delta\tau_2$ denote the polarization dispersion of fibers 1 and 2, respectively.

distortions of, for example, $a_{k2} < -50$ dB, one obtains a maximum bandwidth which may be transmitted. This maximum bandwidth is shown in Fig. 19 as a function of the polarization dispersion $\Delta\tau$ [75]. The assumptions for the wavelength modulation are the same as in Section VI.

If the polarization dispersion is in the order of $\Delta\tau = 20$ ps, a bandwidth of only about 130 MHz or 500 MHz may be transmitted by use of a multilongitudinal-mode laser or by a single-longitudinal-mode laser, respectively.

Due to the wavelength dependence of the delay through the fiber, jitter effects must also be considered (with the maximum jitter in Fig. 18 being $\Delta\tau_2$). Similar jitter effects are also likely to occur parallel to modal noise effects in multimode fibers but nothing has been published yet on that subject.

Any wavelength dependence of the delay may also yield excess noise [75] like the partition noise in connection with material dispersion. If the polarization dispersion is in the same order as the delay difference between adjacent lasing modes in the case of material dispersion a similar excess noise is to be expected. Therefore, for low values of the polarization dispersion low excess noise is also expected.

VIII. Conclusions

The major sources of noise and distortions in optical fiber communication systems have been discussed. In order to design a system with low distortions and low noise by using an index-guided single-longitudinal-mode laser one requires an optical isolator between laser and fiber in order to avoid reflections and a single-mode fiber as the transmission medium in order to avoid modal noise phenomena, but this single-mode fiber should be either low-birefringent or polarization-maintaining in order to avoid the phenomena due to polarization coupling. Alternatively, one may use a gain-guided multilongitudinal-mode laser as the source and a multimode fiber as the transmission medium. In that case, the reflections as well as modal noise may just be tolerated and no optical isolator is required. A system of the latter kind has been installed in Berlin [26] delivering two TV and two FM channels simultaneously to the households. A simple direct intensity modulation scheme for the frequency-multiplexed channels is used exhibiting sufficiently low noise and distortions so that the German cable-TV regulations are met.

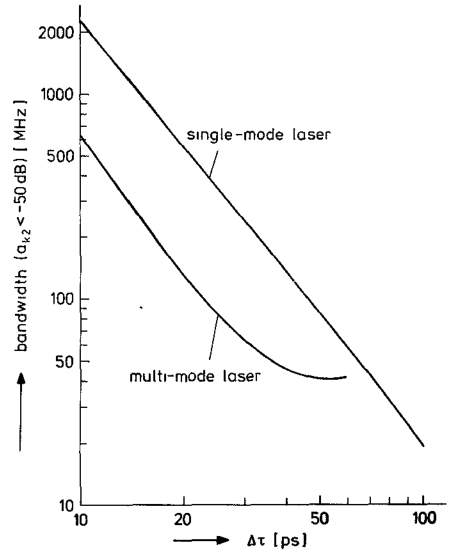

Fig. 19. Maximum bandwidth which may be transmitted with low distortions along a single-mode fiber transmission line with polarization dispersion $\Delta\tau$. Assumptions: Transmission line model according to Fig. 17 with $\alpha = \pi/4$ and $\Delta\tau_1 = \Delta\tau_2 = \Delta\tau$. Both fundamental modes of fiber I are equally excited by the source.

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Spectral Characteristics of Semiconductor Lasers with Optical Feedback

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Abstract—**Optical feedback-induced changes in the output spectra of several GaAlAs lasers operating at 0.83 μm are described. The feedback radiation obtained from a mirror 60 cm away from the laser is controlled in intensity and phase. Spectral line narrowing or broadening is observed in each laser depending on the feedback conditions. Minimum linewidths observed with feedback are less than 100 kHz. Improved wavelength stability is also obtained with optical feedback resulting in 15 dB less phase noise. An analytical model for the three-mirror cavity is developed to explain these observations.**

I. Introduction

The spectral characteristics of single-mode semiconductor lasers are important in determining the performance of optical fiber transmission systems and optical fiber sensors. Narrow spectral linewidth and low frequency wavelength stability are particularly vital in optical heterodyne communication systems [1] and interferometric fiber sensors with a large pathlength difference [2], [3].

Changes in the spectral characteristics of a single-mode laser occur when a portion of the laser output is fed back into the laser cavity after reflection from an external mirror, grating, or a fiber end. Feedback-induced effects previously observed are linewidth broadening [4], [5], line narrowing [6], [7], and reduction of low frequency wavelength fluctuations [8]. As shown in Fig. 1, the external reflector extends the normal laser cavity. The resulting cavity is composed of three mirrors; these include the two end facets of the semiconductor laser separated by a distance l, and the external reflecting surface that is a distance L from the laser diode. The reflectivity of the end facets on the laser are R_0 and R_1, respectively, and the external reflector has a reflectivity r.

Here we report the theoretical and experimental results on the effect of feedback on laser diode emission characteristics. Formulas for predicting the presence of external cavity modes and for feedback-induced line narrowing and phase noise

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