spot intensity with a microscope photosensor shows that the intensity profile is similar to an Airy pattern. The intensity drops to 10% on a diameter of $2.2\,\mu$m. Similar gratings with the same focus distance but smaller grating area show larger, nearly circularly symmetric and mainly diffraction-determined spots; gratings with larger area lead to asymmetric spots caused by mainly by aberrations.

In conclusion, we have optimized a holographic interferometric setup at wavelength $\lambda = 457.9$ nm to achieve with freely propagating wave fronts and conventional optical elements two-dimensional focusing grating couplers at the wavelength $\lambda = 632.8$ nm. Experimental grating couplers with spot diameters of $2.2\,\mu$m have been achieved.

Dr. R. V. Pole has tragiclly crashed in a plane and is believed dead. I am deeply grieved by the loss of a valued colleague. The idea of an integrated optical head was suggested by him. I hope that, if he were still alive, the way I realized this idea and the contents of this letter would meet his approval.

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[1] M. L. Dakss *et al.*, Appl. Phys. Lett. **16**, 523 (1970); H. Kogelnik and T. P. Sosnowski, Bell Syst. Tech. J. **49**, 1602 (1970).

[2] A. C. Livanos *et al.*, Appl. Phys. Lett. **30**, 519 (1977); A. Katzik *et al.*, IEEE J. Quantum Electron. **QE-13**, 296 (1977).

[3] P. K. Tien, Opt. Lett. **1**, 64 (1977).

[4] T. Suhara *et al.*, Opt. Commun. **19**, 353 (1976); W. W. Ng *et al.*, IEEE Trans. Electron. Devices **ED-25**, 1193 (1978); A. Wüthrich and W. Lukosz, Appl. Phys. **21**, 55–64 (1980).

[5] M. Miller and M. Skalsky, Electron. Lett. **15**, 275 (1979).

Noise characteristics of semiconductor laser diodes coupled to short optical fibers

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(Received 13 June 1980; accepted for publication 23 July 1980)

The noise character of semiconductor laser diodes coupled to short optical fibers is found to exhibit increased noise power peaked on the low-frequency side of the intrinsic noise profile. The phenomenon has been observed in laser diodes with and without self-sustained oscillations below 1.8 GHz and can be explained as a downshift in frequency of the intrinsic resonance due to the coupling of the laser cavity and the short optical fiber. This effect may introduce higher noise at frequencies where light-wave communication systems operate even though the laser diodes themselves are very quiet.

PACS numbers: 42.55.Px, 42.80.Mv, 42.60.Da

A semiconductor laser, when irradiated by its own output beam is known to exhibit the so-called "self-coupling" effect,[1-6] in which a periodically modulated noise spectrum is observed with the fundamental frequency determined by the round-trip time of the light along the external cavity. Self-coupling effects have been observed using mirrors,[1-3] gratings,[4,5] and optical fibers[6] to provide the reflections. The reflected-beam-induced modulations often generate annoying signal distortions when the laser diode is modulated and are very undesirable in both analog and digital applications.

In this letter, we report an experimental study of the noise spectrum of AlGaAs laser diodes coupled to short optical fibers. The study is of considerable practical interest since most laser diodes for use in light-wave communications have permanently attached short fiber leads for easy mechanical coupling. We have found that, for a long optical fiber lead, the envelope of the intensity distribution of the modulated noise spectrum is basically governed by the intrinsic resonance profile of the laser diode. We also have found that, for a fiber lead shorter than about 15 cm, reflections can considerably modify the intrinsic noise spectrum, resulting in a substantial increase in noise power and, for some lasers, generate pronounced noise peaks on the low-frequency side of the intrinsic noise profile. We interpret this as being due to a downshift in frequency of the intrinsic resonance due to the coupling of the laser cavity and the short optical fiber. A calculation based on the analysis of Broom *et al.*[1] shows that a feedback of 0.8% of the output power into the laser cavity suffices to account for the observed frequency shift. Our observations indicate that the reflections from a short fiber may introduce higher noise at frequencies where light-wave communication systems operate. We have found that such noise can be effectively suppressed by applying some index matching fluid to fiber-air interfaces.

The experiment consists of launching the output beam of the semiconductor laser diode into a multimode optical fiber. One end of the fiber is formed into a lens using a thermal melting technique.[7] The laser diodes used for this study are oxide-defined, narrow-stripe ($\sim 6\,\mu$m), double-heterojunction AlGaAs structure, operating in the cw mode at 30 °C. The wavelengths of laser emission are between 800–840 nm. The fibers are Corning 62.5-μm-core graded-index multimode fibers with a minimum bandwidth of 200 MHz at 1 km. The launching efficiency is typically 65%. The detector is a Lasermetrics PIN diode which has a 3-dB bandwidth

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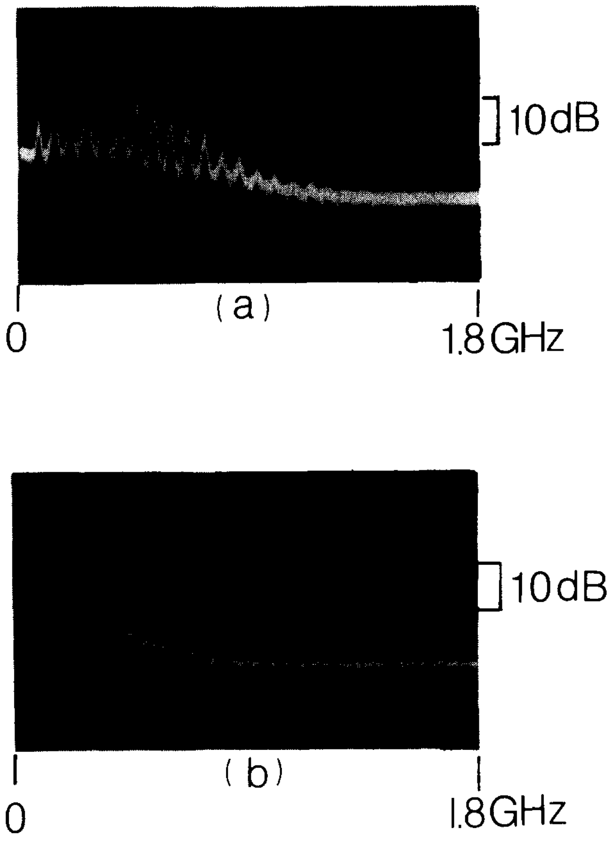

FIG. 1. (a) Noise spectrum of a laser diode coupled to a 146-cm-long optical fiber. (b) Intrinsic noise spectrum of the same laser diode when the optical fiber is not attached. The laser diode is operating at 10% above threshold.

of 700 MHz. The signals from the PIN diode are amplified by a HP 844F wide-band amplifier and displayed on a Tektronix 7L13, 1.8-GHz spectrum analyzer. All measurements were done at a constant photodiode current of 200 μA.

Figure 1(a) shows a typical noise spectrum of a laser diode when coupled to a 146-cm-long fiber. The spectrum is characterized by periodic sharp spikes, the frequenices of which correspond closely to $Nc/2nL$, where n is the index of refraction of the fiber, L is the length of the fiber, and N is an integer.[6] The amplitude of the spikes depends on the laser-fiber coupling efficiency, the finish of the fiber end surface, and any movement of the fiber caused by mechanical vibrations, while the locations of the spikes are relatively insensitive to outside perturbations. The generation of these noise spikes is attributed to selective amplification of those quantum fluctuation frequencies in the laser that match the round-trip time of the optical feedback.[1] In other words, the spikes are the beat notes of the oscillating longitudinal modes of the external fiber cavity. We have found that with increasing injection current, the highest-power spikes shift progressively toward higher frequencies. In laser diodes possessing pronounced noise peaks, the envelope of the noise spikes closely follows the intrinsic noise peak, as is shown in Fig. 1(b).

The picture changes considerably, however, when the fiber is shorter than about 15 cm. In Fig. 2, we show photographs displaying the intrinsic noise spectra of two different laser diodes and the induced-noise spectra of these diodes when coupled to a 3-cm-long fiber. The one shown in Fig. 2(a) is "quiet" and has no self-sustained oscillations below 1.8 GHz, while the one in Fig. 2(c) has. For comparison, the induced-noise spectra of the same laser diodes with optical

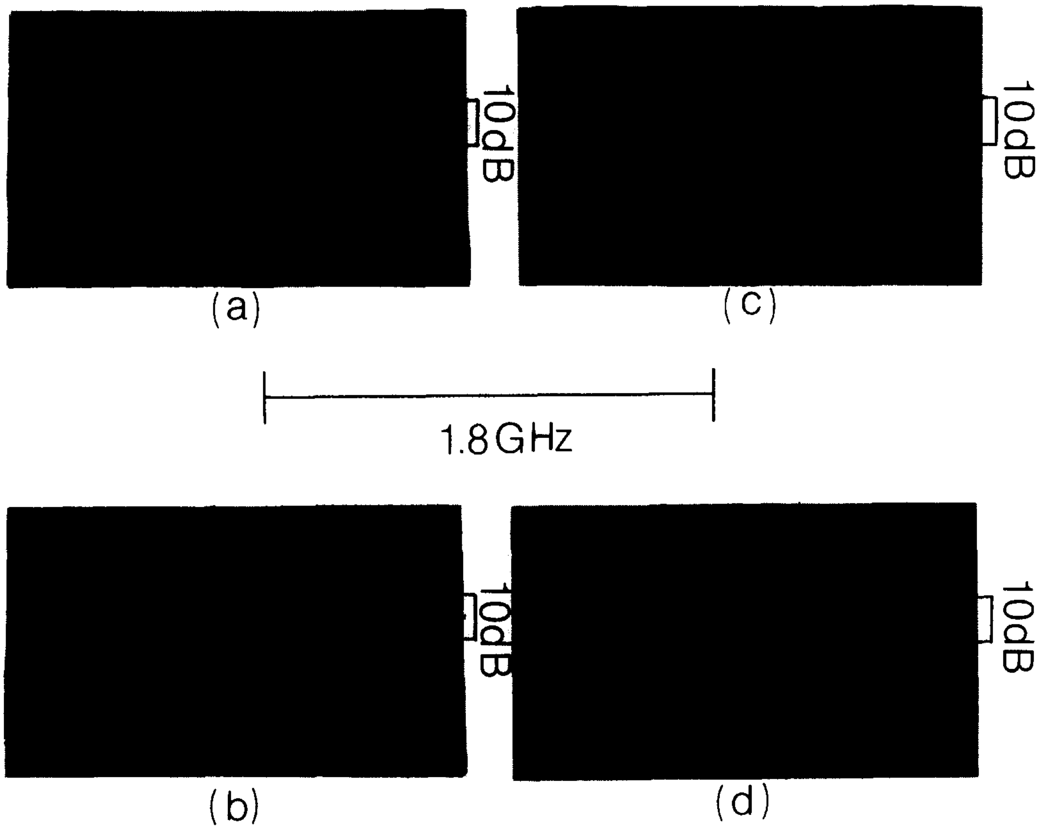

FIG. 2. (a) Intrinsic noise spectrum of a "quiet" laser diode operating at 20% above threshold (upper trace). The lower trace is the background noise of the amplifier. (b) Noise spectrum of the same laser diode operating under the same condition as (a) coupled to a 3-cm-long optical fiber (upper trace). The lower trace is the background noise level of the amplifier. (c) Intrinsic noise spectrum of a moderately pulsating laser diode operating at 20% above threshold, when the optical fiber is not attached. No amplifier is used in the measurement. (d) Noise spectrum of the same laser diode.operating under the same condition as (c) coupled to a 3-cm-long fiber.

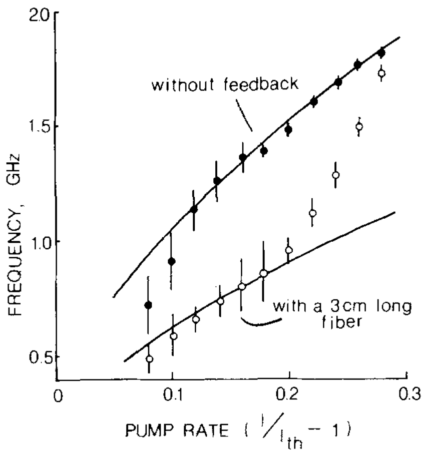

FIG. 3. Experimental and calculated results of peak noise frequency vs pump rate obtained using a self-pulsating laser diode without feedback (dots) and with feedback from a 3-cm-long optical fiber (circles). The error bars stand for the 3-dB linewidth of the noise peaks.

feedback from the fiber are shown in Figs. 2(b) and 2(d). We have found that some laser diodes are more susceptible to reflections than others. Of the "quiet" laser diodes we have tested, only a small fraction are susceptible and exhibit pronounced induced noise peaks similar to that shown in Fig. 2(b). The rest of them merely show an increase (3–10 dB) in low-frequency noise. When additional feedback is provided by reflections from a microscope slide, they exhibit pronounced and somewhat sharpened noise peaks on the low-frequency side of the intrinsic noise profile. Immersing the cleaved end of the fiber into some index matching fluid, such as optical epoxy fluid with $n \approx 1.5$, the spectrum recovers its intrinsic pattern, almost fully, indicating that reflections from the lensed end of the fiber have negligible effect. Wetting the fiber-air interfaces with index matching fluids is therefore a useful technique for suppressing the reflection-induced noise. We have found that the peak noise frequency decreases as the launching efficiency and/or length of the fiber increase. For fiber lengths greater than 10 cm, the peak reduces in size and flattens out considerably with its frequency approaching an asymptotic value of about 200 MHz. With increasing injection current, the peak shifts toward higher frequencies, but more slowly than the intrinsic noise peak. When a long fiber is connected to the short fiber lead, the envelope of the noise spikes caused by the long fiber follows the induced-noise peak.

The effect of an external cavity on the noise character of a semiconductor laser diode has been studied by many authors.[1,4,5,8,9] It has been noted that the external cavity, under proper conditions, can considerably increase the lifetime of the photons inside the laser cavity and therefore lead to a decrease in the intrinsic resonance frequency.[1] We believe that the short-fiber-induced noise peaks we have observed belong in part to this category, since they possess all features expected of a frequency-shifted resonance. In Fig. 3, we present experimental data of resonance frequency versus pump rate ($I/I_{\mathrm{th}} - 1$) measurement made for a moderately pulsating laser diode coupled to a 3-cm-long fiber. The error bars stand for the 3-dB linewidth of the noise peaks. To check if reflections from a cleaved fiber end surface suffice to account for the observed frequency shift, we have calculated the dependence of the resonance frequency on pump rate for a laser-to-fiber coupled system with the fraction of light fed back into the laser cavity as a parameter. The calculation follows the approach of Broom *et al.*[1] when they analyzed self-modulation frequency of a laser diode, with linear gain, coupled to an external Fabry Perot cavity. The parameters used, following the notation of Ref. 1, are $\overline{\alpha} = 10\ \mathrm{cm}^{-1}$, $l = 0.0254$ cm, $\tau_s = 1 \times 10^{-9}$ sec, $R = 0.32$, $R_{\mathrm{ext}} = 0.04$. In Fig. 3 we plot the calculated curves for zero feedback and for 0.8% of the light fed back into the laser cavity. One can see that the calculated curves indeed reflect the general features of the data at small pump rates. The fraction of light fed back into the laser inferred from our analysis is consistent with an estimate made from the reduction in threshold current when the external reflector is used. A large discrepancy between the measured and calculated results exists at large pump rates. In this region, the width of the intrinsic resonance narrows appreciably, marking the onset of the self-sustained oscillations, and the analysis based on the linear gain assumption is probably not adequate.[8] It is also possible that, at large pump rates, the mode character of the laser diode has changed in such a way that a higher feedback is required to maintain the frequency shift predicted by the calculation. Numerical analysis using rate equations with terms accounting for the effects of saturable absorbers[10] or nonlinear gain[11] is currently under way.

The observations reported here indicate that the reflections from a short optical fiber may introduce pronounced noise peaks in frequency regions where light-wave communication systems operate even though the laser diodes themselves are very quiet in those regions. One method of reducing such noise is to use optical isolators between the laser diodes and the transmission lines. Another, easier method that can be used in the laboratory is to eliminate the fiber-air interfaces using index matching fluid. In practical systems, the use of "wet" connectors or splices can greatly reduce the problem.

Thanks are due to P. Zory, A. Reisinger, and D.R. Patterson for many helpful discussions, and to R. Waters and D. Chang (of Columbia University) for comments on the manuscript.

[1] R. F. Broom, E. Mohn, C. Risch, and R. Salath, IEEE J. Quantum Electron. **QE-6**, 328 (1970).

[2] T. Morikawa, Y. Mitsuhasi, J. Shimada, and Y. Kojima, Electron. Lett. **12**, 435 (1976).

[3] Y. Mitsuhashi, T. Morikawa, A. Seko, and J Shimada, Opt. Commun. **17**, 95 (1976).

[4] T. L. Paoli, J. E. Ripper, A. C. Morosini, and N. B. Patel, IEEE J. Quantum Electron. **QE-11**, 525 (1975).

[5] C. Risch and C. Voumard, J. Appl. Phys. **48**, 2083 (1977).

[6] I. Kushima and M. Maeda, IEEE J. Quantum Electron. **QE-14**, 331 (1978).

[7] D. Kato, J. Appl. Phys. **44**, 2756 (1973).

[8] L. Figueroa, K. Lau, and A. Yariv, Appl. Phys. Lett. **36**, 248 (1980).

[9] H. Kuwahara, Appl. Phys. **20**, 67 (1979).

[10] R. W. Dixon and W. B. Joyce, IEEE J. Quantum Electron. **QE-15**, 470 (1979).

[11] J. P. van der Ziel, J. L. Merz, and T. L. Paoli, J. Appl. Phys. **50**, 4620 (1979).