Suppression of RF Noise Tones Caused by Rayleigh Backscatter in to an Unisolated Laser Using Audio-Frequency External Optical-Phase Modulation

Hongbing Gan, Arthur J. Lowery, *Senior Member, IEEE,* and Richard D. T. Lauder, *Member, IEEE*

***Abstract*— When Fabry–Perot lasers are subject to Rayleigh backscatter, dramatic line-narrowing and frequency hopping up to 500 MHz, evidenced by radio-frequency (RF) tones, are observed. These RF tones will severely degrade the system performance of a subcarrier multiplexed transmission system, such as quadrature phase-shift keying. In this letter, it is demonstrated that audio-frequency external optical-phase modulation can suppress the noise tones and restore the laser linewidth. This scheme may offer an inexpensive alternative to optical isolators to recover the system performance and thus is very important for cost-effective customer access networks.**

***Index Terms*—Audio frequency, customer access network, noise suppression, optical-phase modulation, Rayleigh backscatter.**

I. INTRODUCTION

OPTICAL feedback such as Rayleigh backscatter (RB) and discrete reflections induce instability in lasers and degrade system performance. Reflections from connectors and fiber end faces can be suppressed to better than −55 dB with angle-cleaved FC connectors. However, RB cannot be avoided unless optical isolators are used. Optical isolators significantly increase the cost of access systems and so are not desirable.

Goldberg *et al*. [1] first studied the effects of feedback on a laser diode from RB, observing a linewidth reduction of more than 200-times and wavelength instability on a millisecond scale. They attributed the frequency hopping to small random thermal fluctuations in the fiber. Mark *et al*. [2], [3] presented a statistical model which gave a good estimate of the measured frequency distribution for a 1.3-μm laser diode exposed to RB from 760-m of single-mode fiber. Line narrowing was attributed to RB, which was shown to establish a sharp frequency-selective reflection to which the laser would lock. However, unavoidable thermal and mechanical perturbations in the fiber caused the center lasing frequency to jitter randomly up to 1 GHz. The linewidth was measured as a function of fiber length and laser-to-fiber coupling efficiency, and was less than 0.1 Hz for a 1420-m fiber with a coupling efficiency of 0.2. A good estimate of linewidth and lasing frequency distribution was obtained from a simple analytical expression. Similar results were measured by Chraplyvy *et al*. [4] for the spectral behavior of a 1.5-μm InGaAsP DFB laser subject to RB from a single-mode fiber. The probability distribution of frequency was approximated by a Gaussian distribution with a width proportional to the laser-fiber coupling efficiency. Laser frequency excursions up to 1 GHz were observed. The experiment agreed well with theory based on a Van der Pol oscillator model. They also reported that during a frequency transition, the laser could actually have a mixture of the two frequencies evidenced by the appearance of sharp tones (beat notes) on a radio-frequency (RF) spectrum analyzer. Such beat notes would cause errors in a lightwave transmission system using modulation schemes such as binary-phase-shift keying (BPSK), quadrature-phase-shift keying (QPSK), and quadrature amplitude modulator (QAM).

LaViolette [5] recently investigated the impact of RB induced RF noise on QPSK transmission which is commonly used in customer access networks. A 14-dB carrier-to-noise ratio (CNR) penalty (carrier frequency 19 MHz, data rate 1.544 Mb/s) at 1×10^{-8} bit-error rate (BER) was found, which was caused by laser sporadic noise generated by RB into the laser from the fiber. To show the bit errors were caused by RB, the fiber was first replaced with an optical attenuator, and then an optical isolator was inserted between the laser and the fiber. All the connectors were angle-cleaved which had return loss better than −55 dB. It was expected that the system performance in these two cases would be limited by test equipment performance. It was clearly shown that the 14-dB CNR penalty was caused by RB from the fiber [5], as the optical isolator and attenuator removed the BER penalty.

In this letter, we demonstrate that the RF noise can be reduced by applying audio-frequency optical-phase modulation to the fiber close to the laser, using a simple inexpensive transducer. We also observe and explain a reduction in the mean RB power when the modulation is applied. Our scheme may offer a cheap alternative to the use of optical isolators, which is important in cost-effective customer access networks such as the upstream optical path of a hybrid-fiber-coax (HFC) network.

II. EXPERIMENT

The experiment was set up, as shown in Fig. 1, to observe the noise-inducing effects of RB on an unisolated laser and

---

Manuscript received June 1, 1998; revised June 9, 1998. This work is partly supported by Telstra Research Lab, a division of Telstra Corporation.

The authors are with the Australian Photonics Cooperative Research Centre, Photonics Research Laboratory, Department of Electrical and Electronic Engineering, The University of Melbourne, Parkville, VIC 3052, Australia.

Publisher Item Identifier S 1041-1135(98)08771-0.

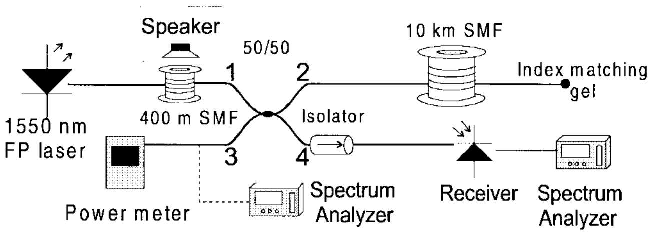

Fig. 1. Experimental setup.

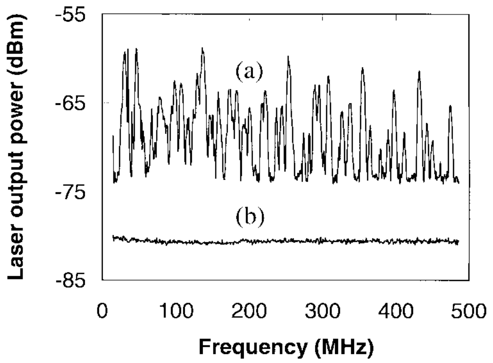

Fig. 2. RF spectrum of laser output (measured at port 4 of the coupler in Fig. 1.) (a) RF noise tones when laser subject to RB (maxholding function of RF spectrum analyzer used for one minute). (b) RF noise tones suppressed when acoustic modulation was applied (no maxholding). (Resolution bandwidth: 2 MHz.)

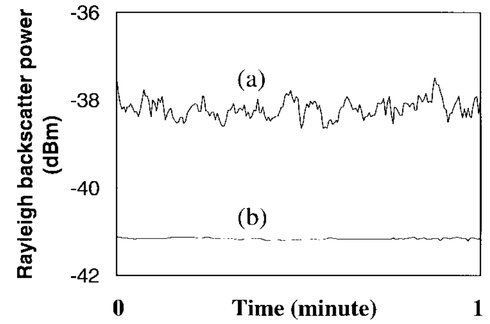

Fig. 3. RB power level (a) when the laser was subject to RB (b) when the acoustic modulation was applied.

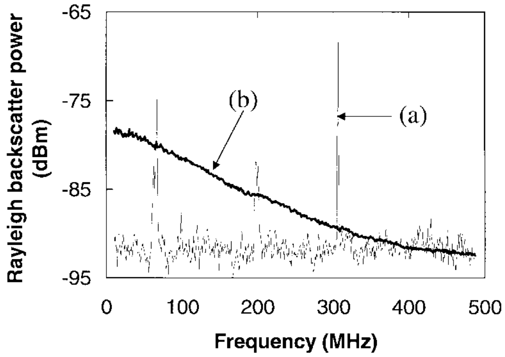

Fig. 4. RF spectrum of interferometric RB indicating laser linewidth (measured at port 3 of the coupler in Fig. 1.) (a) Narrow-linewidth modes beat producing tone bursts when phase modulation off (b) laser goes to free-running when phase modulation on. (Resolution bandwidth: 2 MHz.)

its suppression using cheap devices. A Fujitsu FLD150C2KM 1550-nm Fabry-Perot laser was biased with 25-mA dc current and generated −2.5 dBm optical power. Its output was coupled to port 1 of a 50/50 coupler via 400 m of standard single-mode fiber (SMF). Port 2 of the coupler was fusion spliced to 10 km of standard SMF with the fiber's far end immersed in index matching gel to suppress Fresnel reflection; thus RB was the dominant feedback to the unisolated FP laser. Port 3 of the coupler was used to monitor the RB. Port 4 of the coupler was used to monitor the laser output.

Firstly, the effects of RB on the unisolated laser were measured. The RF spectrum of the laser output showed random frequency tones as high as 20 dB above the noise floor from dc to 500 MHz when the laser was subject to RB, as shown in Fig. 2(a). The "maxholding" function of the spectrum analyzer was used for one minute. To show that these random frequency tones were caused by RB, a 15-dB bending loss was applied at the transmission end of the 10-km fiber and this removed these tones. This result is consistent with the results published in [1]–[5]. These tones are ascribed to mode hopping between external cavity modes, with the external cavity resulting from a superposition of the reflections from the many scattering centers [1]–[4]. During a transition, the laser has two lasing frequencies, and the tones are caused by mixing at the photodiode [4]. The laser linewidth was estimated to be around 1 kHz by measuring the width of RF tones when the laser was subject to RB. Large linewidth-narrowing can be explained as the RB establishes a narrow bandwidth reflection. The laser locks to this reflection and then has a very narrow linewidth due to the long effective cavity. Interestingly, the absolute power level of the RB monitored from port 3 fluctuated on a time-scale comparable to 1 s, as shown in Fig. 3(a).

Secondly, a 0.25-W loudspeaker seated on the fiber spool was driven by a 500-Hz 150-mA electrical signal. The electrical input power was 180 mW and the generated audio output power was 58 dB. When an acoustic wave is incident on the fiber, the resulting changes in fiber length, diameter and refractive index cause a variation in optical phase due to the photoelastic effect [6]. Thus the laser output was optical-phase modulated by the acoustic wave, as was the backscattered light. Under the optical-phase modulation, the RF spectrum of laser output showed no RF tones as shown in Fig. 2(b), measured at port 4 of the coupler. The RF spectrum of RB, as shown in Fig. 4, was measured at port 3 of the coupler. The RF spectrum of RB (showing laser linewidth because RB is interferometric multipath signal) indicated that linewidth-narrowing was also suppressed; the laser linewidth increased to 110 MHz. As shown in Fig. 3(b), the RB power monitored from port 3 was reduced by 3 dB to −41 dBm and the second time-scale power fluctuations disappeared.

Finally, an optical isolator was inserted immediately after the FP laser to prevent RB from entering the laser. With the isolator in place, it was observed that the RF spectrum, linewidth and power level were the same as when the fiber was optical-phase modulated by an acoustic wave. Thus the acoustic (optical-phase) modulation mimics the optical isolator in suppressing the unwanted interaction between the RB and the laser, which causes the RF noise tones.

III. Discussion

The FP laser in this experiment had a free-running linewidth of 110 MHz, and linewidth was estimated to be around 1 kHz when the laser was subject to RB. RB thus establishes a sharp frequency-selective reflectivity, acting as a resonator with a very high Q resonance, to which the laser locks with a narrowed linewidth [7]. The laser-fiber configuration is an excellent narrow-linewidth source, but only over short time scales due to thermal and mechanical fluctuations within the 10-km optical fiber, which continuously change the frequency of peak reflectivity. The laser continuously tries to lock to this frequency. The laser-fiber configuration will thus switch between external cavity modes on a long time-scale. During switching, two modes will co-exist. These are likely to be close in frequency as they are likely to be within the dominant laser-chip mode, and thus will beat to give RF tone bursts.

When an acoustic wave is applied to the 400-m fiber, the RB light is optical-phase modulated before it enters the laser cavity. It is clear that the externally applied optical-phase modulation breaks the laser-RB phase-locking state. The optical-phase modulation spreads the optical spectrum, making it much wider than an external cavity resonance. The laser can no longer lock to the sharp frequency-selective reflectivity. The laser goes to its free-running state, evidenced by the restoration of laser linewidth to 110 MHz as shown in Fig. 4(b), measured at port 3 of the coupler. Thus pure RF tones due to two narrow-linewidth modes beating disappear. The RB power level stops fluctuating. The reduction in the mean RB power (Fig. 3) can be explained by noting that the laser tries to follow the frequency of high RB reflectivity when the optical-phase modulation is off. Thus, the reflected power will be high if this is achieved. The power fluctuations show that the laser takes time to lock to this reflectivity. When the optical-phase modulation is on, the laser is not locked to a peak reflectivity. Furthermore, the broad laser linewidth averages the reflectivity over a large frequency interval, thus reducing fluctuations.

IV. Conclusion

This experiment demonstrates that audio-frequency external optical-phase modulation using acoustic waves can break the laser-RB phase-locking condition by spreading the optical spectrum. The sharp frequency-selective reflectivity imposed by RB is ineffective because the phase modulation ensures that there is insufficient time for phase-locking to be achieved. The laser linewidth goes to its free-running value. Most importantly, the lasing frequency stops hopping between external-cavity modes, and hence the RF frequency tones are suppressed. Direct modulation can also break the phase-locking condition by frequency chirping, thus explaining why frequency tones disappear in direct intensity modulated systems that are not idling. However, in subcarrier transmission systems such as QPSK [5], the optical modulation index can be very low (around 5% or lower), in which case the phase-locking condition is not broken. Furthermore, some systems allow their lasers to be unmodulated when data is not present. If the unmodulated channel is subcarrier-multiplexed with other channels, the RF tones will degrade the performance of these other channels. The scheme used in this experiment can effectively suppress the RF noise tones caused by RB, and thus may offer an inexpensive alternative to optical isolators in cost-effective customer access networks. This work represents a first proof of principle. Further work toward a compact prototype, such as optimizing the modulation frequency, maximizing the coupling between acoustic wave and fiber, and minimizing the required input power, is under development.

References

[1] L. Goldberg, H. F. Taylor, and J. F. Weller, "Feedback effects in a laser diode due to Rayleigh backscattering from an optical fiber," *Electron. Lett.*, vol. 18, no. 9, pp. 353–354, 1982.

[2] J. Mark, E. Bodtker, and B. Tromborg, "Statistical characteristics of a laser diode exposed to Rayleigh backscatter from a single-mode fiber," *Electron. Lett.*, vol. 21, no. 22, pp. 1010–1011, Oct. 1985.

[3] ——, "Measurement of Rayleigh backscatter-induced linewidth reduction," *Electron. Lett.*, vol. 21, no. 22, pp. 1008–1009, Oct. 1985.

[4] A. R. Chraplyvy, D. Marcuse, and R. W. Tkach, "Effect of Rayleigh backscattering from optical fiber on DFB laser wavelength," *IEEE J. Lightwave Technol.*, vol. LT-4, pp. 555–559, May 1986.

[5] K. D. Laviolette, "The impact of Rayleigh backscatter induced noise on QPSK transmission with Fabry-Perot lasers," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 706–708, May 1996.

[6] S. A. Kingsley and D. Davies, "Multimode optical fiber phase modulators and discriminators: I-Theory," *Electron. Lett.*, vol. 14, pp. 322–324, 1978.

[7] P. Gysel and R. K. Staubli, "Spectral behavior of directly modulated laser diodes exposed to Rayleigh backscatter from a single-mode fiber," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 207–209, Mar. 1991.