Brillouin Scattering in Externally Modulated Lightwave AM-VSB CATV Transmission Systems

X. P. Mao, G. E. Bodeep, R. W. Tkach, A. R. Chraplyvy, T. E. Darcie, and R. M. Derosier

Abstract—**We measure the stimulated Brillouin scattering threshold for a CW laser externally modulated with an AM-VSB CATV signal. The threshold is essentially unchanged from the unmodulated case. For injected powers above the threshold power, substantial degradation of the carrier to noise ratio is seen.**

RECENTLY, there has been great interest in lightwave systems for the transmission of cable television signals. The format most commonly used is amplitude modulation vestigial sideband (AM-VSB) where the usual CATV electrical signal is imposed as intensity modulation on the optical wave. The requirements on laser noise and linearity in such systems are quite severe. External modulation of CW lasers offers a source, which is in principle free of second harmonic distortion, one of the major factors degrading linearity [1]. Such a source also has a compact optical spectrum, which while ameliorating distortion due to dispersion [2], can enhance the effect of optical nonlinearities, especially stimulated Brillouin scattering (SBS). SBS converts the transmitted signal in the fiber to a backward scattered one, and thus sets a limit to the total fiber injected power. Without modulation, the SBS threshold power is on the order of a few mW [3]. This process is narrowband, with an inherent linewidth of 20 MHz at 1.5μm, so that the threshold increases in proportion to the spectral width of the source. Directly modulated DFB lasers for this application have a spectral width under modulation on the order of 1 GHz, which results in thresholds in the hundred mW range. In a lightwave AM-VSB CATV transmission system, the total system loss budget is small (< 10 dB) since a high carrier to noise ratio must be maintained for 40–60 channels, while the modulation index for any one channel is only a few percent. Since these systems are primarily shot noise limited, this in turn leads to a desire to operate at as high a launched power as possible. Thus, the occurrence of SBS, which limits the transmitted power, places a limit on system length or loss.

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X. P. Mao was with AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733. He is now with Polytechnic University, Brooklyn, NY 11201.

G. E. Bodeep, R. W. Tkach, A. R. Chraplyvy, T. E. Darcie, and R. M. Derosier are with AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733.

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In this letter, we describe the measurements of the SBS threshold in an optical AM-VSB CATV transmission system, using a narrow-linewidth *F*-center laser. For a modulation index of 4% per channel and 42 channel transmission, the SBS threshold is about 4 mW, which is almost identical to that of the unmodulated case. In addition to the system impact of this limitation to launched powers below 4 mW, we have measured the carrier-to-noise ratio (CNR) as a function of the fiber injected power. We find that the CNR improves with power until the launched power reaches the SBS threshold. After this point, increases in launched power actually degrade the CNR.

Experiment

The experimental setup is similar to the arrangement used earlier to measure SBS threshold dependence on fiber parameters [4]. Light from a single-frequency *F*-center laser is passed through an optical isolator, a variable optical attenuator and a polarization controller. The modulator employed is a $LiNbO_3$ Mach-Zehnder interferometer type driven by a standard AM-VSB CATV signal. The modulated light is injected into the first optical coupler which passes 90% of the light to the test fiber and the remainder to a 3 dB coupler used for obtaining the reference power and for diagnostics. Three power meters allow simultaneous measurement of the output power from the test fiber, and forward and backward reference powers (allowing calculation of the injected and scattered powers). A Fabry–Perot interferometer is used to ensure that the laser is operating on a single mode. Optical reflections arising from fiber ends, splices, and other interfaces must be kept below -35 dB to obtain accurate threshold measurements. The injected power is varied with an optical attenuator and all three powers are recorded. When measuring the excess noise in the forward direction, the transmitted signal is detected by an optical receiver and then measured by an RF spectrum analyzer. The test fiber is a 13-km length of dispersion shifted fiber, with a core area of 35 μm^2.

Fig. 1 shows a plot of transmitted and scattered power versus injected power. The powers indicated on the figure have been calibrated to correspond to injected power in the test fiber, total scattered power at the input end of the test fiber, and output power from the test fiber. Without modulation, the measured threshold as indicated by the solid circles on the figure is about 4 mW. Transmitted power is limited to

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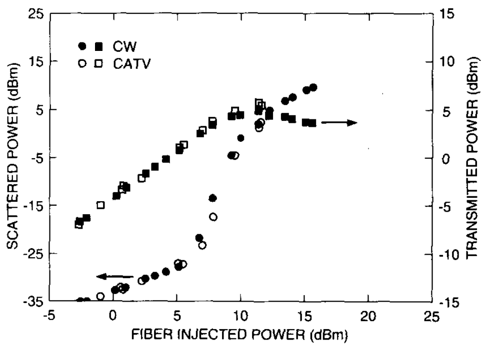

Fig. 1. Plot of scattered and transmitted power versus injected power for a 13-km length of dispersion-shifted fiber, with and without 42 channel AM-VSB modulation.

less than 3 mW above the threshold. The open circles show the behavior when the light is modulated with a modulation index of 4% for each of 42 channels. Very little change in SBS threshold was seen, compared to the unmodulated case. This implied that the fiber injected power is still mainly concentrated in the main optical carrier despite the modulation. This has been verified theoretically by calculating the modulated optical spectrum and evaluating the SBS threshold: modeling the AM-VSB signal as a zero-mean Gaussian process [5], we find that the optical spectrum retains 99% of the power in the carrier, with the remaining 1% distributed in sidebands corresponding to the modulation. This then corresponds to a SBS threshold increase of 0.04 dB over that observed for an unmodulated laser. Thus, CATV transmission systems using external modulation must operate at injected power levels below the CW threshold for SBS. This threshold is given by [6]

$$P_{\text{th}} = \frac{21 A\alpha}{\gamma(1 - e^{-\alpha L})}$$

where A is the core area (cm^2), $\alpha(\text{cm}^{-1})$ is the fiber loss, $\gamma = 2 \times 10^{-9}$ cm/W is the Brillouin gain coefficient, and L(cm) is the fiber length. For example, for systems operating over 20 km of conventional step-index depressed-cladding single-mode fiber at 1.3 μm, injected powers must be kept below 9 mW. This number decreases for longer lengths, if the wavelength is changed to 1.5 μm, or for dispersion shifted fiber[4].

In addition to this limitation of injected power, we have investigated the effect of SBS on the quality of the signal which reaches the receiver. Fig. 2 is a plot of noise spectral density output from the receiver at a frequency of 67.25 MHz versus power injected to the fiber. The laser is unmodulated in this case. When the test fiber is replaced by a short jumper (too short for SBS or other nonlinearities to occur) and attenuation to match the loss of the test fiber, we observe the noise performance of the receiver. At low powers thermal noise sets a constant noise floor. As power is increased, shot noise from the received optical power becomes the limiting noise source. The solid line is a theoretical prediction of the combination of shot noise and thermal noise. When the

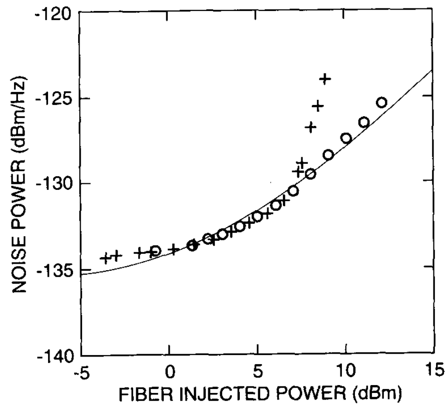

Fig. 2. Plot of transmitted noise power versus injected power with and without 13-km fiber. Without 13-km fiber, the fiber injected power in horizontal axis corresponds to the received power plus fiber loss of 4 dB.

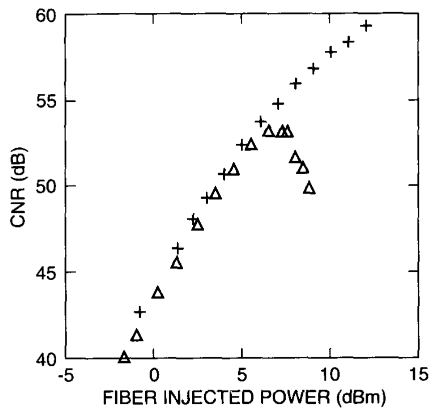

Fig. 3. Plot of CNR versus fiber injected power with and without 13-km fiber. Without 13-km fiber, the fiber injected power in horizontal axis corresponds to the received power plus fiber loss of 4 dB.

13-km test fiber is present, we see a sharp increase in noise when the SBS threshold is exceeded. Fig. 3 shows the measured carrier-to-noise ratio (CNR), referred to a 4 MHz bandwidth, as a function of power injected to the test fiber. This measurement was made with modulation of the source corresponding to one video channel at 67.25 MHz. A single channel was used in order to eliminate noise from intermodulation products produced in the receiver at high received power levels. As described above, this has no effect on the SBS threshold since the threshold under 42 channel modulation is virtually identical to that with no modulation at all. With the test fiber replaced with the jumper and attenuator as above, increasing fiber injected power increases the CNR. With the 13-km fiber, at low power levels, the CNR grows proportionally to the fiber injected power. Brillouin scattering in this region is negligible and the measured noise power is first from the thermal noise in the receiver, and as power increases above 1 dBm, shot noise. As the injected power increases beyond 6 dBm, a rapid degradation in CNR occurs. Fig. 4 plots the CNR with the test fiber along with the power scattered in the backward direction. From this figure we can

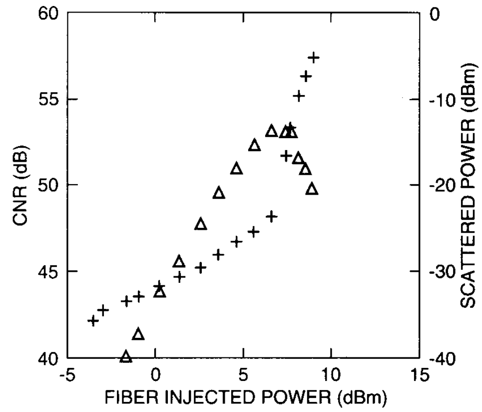

Fig. 4. Plot of CNR and backscattered power versus fiber injected power.

clearly see that the degradation in CNR begins at the SBS threshold.

In summary, we have measured the SBS threshold in an externally modulated lightwave AM-VSB CATV transmission system. The threshold is virtually independent of modulation for a modulation index of 4% with 42 channels. This leads to an upper limit of a few to several mW of launched power depending on system parameters. We have also observed substantial excess noise arising from Brillouin scattering for injected powers above threshold. This excess noise effect may be the first effect of SBS to be noticed in systems since backward scattered power is not usually monitored.

References

[1] T. E. Darcie and G. E. Bodeep, "Lightwave subcarrier CATV transmission systems," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 524-533, May 1990.

[2] M. R. Phillips, T. E. Darcie, D. Marcuse, G. E. Bodeep, and N. J. Frigo, "Nonlinear distortion generated by dispersive transmission of chirped intensity-modulated signals," *IEEE Photon. Technol. Lett.*, vol. 3, p. 481, 1991.

[3] A. R. Chraplyvy, "Limitations on lightwave systems due to optical nonlinearities," *J. Lightwave Technol.*, vol. 8, p. 1548, 1990.

[4] X. P. Mao, R. W. Tkach, A. R. Chraplyvy, R. M. Jopson, and R. M. Derosier, "Stimulated Brillouin threshold dependence on fiber type and uniformity," *Tech. Dig. OFC' 91*, p. 41, 1991, *IEEE Photon. Technol. Lett.*, vol. 4, p. 66, 1992.

[5] Thomas E. Darcie, George E. Bodeep, and A. M. Saleh, "Fiber-reflection-induced impairments in lightwave AM-VSB CATV systems," *J. Lightwave Technol.*, vol. 9, p. 991, 1991.

[6] R. G. Smith, "Optical power handling capacity of low-loss optical fibers as determined by stimulated Raman and Brillouin Scattering," *Appl. Opt.*, vol. 11, pp. 2489-2494, 1972.

Practical TV Channel Capacity of Lightwave Multichannel AM SCM Systems Limited by the Threshold Nonlinearity of Laser Diodes

C. J. Chung and Ira Jacobs

Abstract—**Experimental measurements of clipping-induced nonlinear distortion due to over modulation of laser diodes in multichannel AM SCM systems are shown to be in good agreement with recent theory and simulation results. These results are then used to show that the number of channels, consistent with CATV distortion and noise requirements in presence of threshold nonlinearity, relative intensity noise, and receiver thermal noise, are higher than previous estimates. The sensitivity of these results with respect to the carrier-to-noise ratio requirement and the received optical power at the photodetector is also discussed.**

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The authors are with the Fiber & Electro-Optics Research Center, the Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.

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Introduction

Amplitude modulated subcarrier multiplexed systems (AM SCM) are attractive for lightwave multichannel video transmission because of their direct compatibility with the National Television Systems Committee (NTSC) amplitude modulated vestigial-sideband (AM VSB) format [1]-[3]. However, such systems require higher carrier-to-noise (CNR) and lower nonlinear distortion (NLD) than systems employing frequency or digital modulation techniques. Consequently, lightwave AM SCM systems generally have a limited-channel capacity and low optical power margin.

Saleh [4] has made an important contribution by identifying the threshold nonlinearity of laser diodes as a fundamental limitation in AM SCM systems, and by providing an

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