Repeaterless Transmission of 80-Channel AM-SCM Signals Over 100-km Large-Effective-Area Dispersion-Shifted Fiber

C. C. Lee and S. Chi

***Abstract*—We have investigated the SBS threshold and transport of AM-SCM signal over large-effective-area dispersion-shifted fiber (LEAF), truewave/reduced slope fiber, and standard single-mode fiber with external modulation. The transmission performance of $\mathrm{CNR} \geq 49.4$ dB, $\mathrm{CSO} \leq -60.5$ dB, and $\mathrm{CTB} \leq -60.3$ dB has been achieved for externally modulated 80-channel AM-SCM signals over 100-km LEAF without in-line optical amplifiers.**

***Index Terms*—CATV, LEAF, SCM.**

I. INTRODUCTION

SUBCARRIER multiplexing (SCM) technique is widely used in lightwave amplitude modulation vestigial sideband (AM-VSB) CATV systems. External modulation of a continuous-wave (CW) laser offers a source to have a compact optical spectrum, which can alleviate the second-harmonic distortion due to fiber dispersion. If external modulators together with erbium-doped fiber amplifiers (EDFA's) are used, the increased optical power and lower fiber attenuation at 1550 nm can lead to significantly increased transmission distance. However, the narrow spectral width of such a transmitter combined with the high EDFA output power results in stimulated Brillouin scattering (SBS) which limits the injected optical power in fiber and places a limit on system length or loss [1], [2]. SBS generates large intensity noise and introduces additional distortion [3]. When the high optical power is injected into the fiber, the intermodulation distortion generated by the fiber nonlinearity and dispersion also needs to be considered [4]. Large-effective-area dispersion-shifted fiber (LEAF) offers low Kerr nonlinearity and chromatic dispersion, thus allows larger signal power and longer repeater spacing in both nonreturn-to-zero (NRZ) and soliton systems [5]. The Brillouin-gain spectrum of LEAF has three-peak structure with lower gain, therefore the stimulated Brillouin scattering (SBS) threshold power is increased. LEAF, which has low dispersion, high SBS threshold power and low attenuation loss, is expected to have good performance in the 1550-nm externally modulated AM-SCM systems.

In this letter, we investigate the feasibility of the multichannel AM-VSB signal delivery over long LEAF link without in-line optical amplifiers. The Brillouin-gain spectra and transmission performances of LEAF, truewave/reduced slope fiber (TWF) and standard single-mode fiber (SMF) are measured and analyzed. System experiment of 80-channel AM-SCM signal transmission over a 100-km LEAF without in-line optical amplifiers is also demonstrated.

Manuscript received July 30, 1999; revised October 13, 1999.

C. C. Lee is with the Chunghwa Telecom Labs., P.O. Box 6-1, Yang-Mei 326, Taoyuan, Taiwan (e-mail: chchl@ms.chttl.com.tw).

S. Chi is with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan.

Publisher Item Identifier S 1041-1135(00)01356-2.

II. ANALYSIS

A. SBS Threshold

When SBS occurs in an optical fiber, the carrier-to-noise ratio (CNR) and composite second-order distortion (CSO) are seriously degraded in AM-SCM systems. Therefore, the injected signal power into the fiber is limited by the SBS threshold. From the analysis of [2], the SBS threshold for lasers modulated with AM-SCM signals is only little higher than unmodulated lasers. Therefore, the SBS threshold for CATV AM-VSB systems can be regarded as the SBS threshold in the case of CW laser source. For CW light with a laser linewidth much narrower than the Brillouin gain bandwidth of fiber, the SBS threshold P_t in the optical fiber with uniform Brillouin gain along its length is given by [6]

$$P_t \cong 21 \frac{K A_{\mathrm{eff}}}{g_B L_{\mathrm{eff}}} \tag{1}$$

where

- K is the polarization factor,
- A_{eff} is the effective core area,
- g_B is the maximal Brillouin gain, and
- L_{eff} is the effective interaction length.

LEAF has a refractive-index profile of a trapezoid surrounded by a step ring [7]. Different composition or doping concentration in the core of LEAF produces different acoustic velocities, and multipeak Brillouin spectrum is expected. The fiber with larger A_{eff} and less g_B will offer the larger SBS threshold for CATV AM-VSB signal transmission.

B. Intermodulation Distortion

If the laser is externally modulated with chirp-free by a single tone with frequency Ω, the second-harmonic distortion (2HD), which is induced by fiber dispersion and nonlinear refractive index and larger than the third-harmonic distortion, can be described by [4]

$$2\mathrm{HD} = \frac{1}{4} m \ddot{\beta}^2 z^2 \Omega^4 - \frac{1}{2} m \ddot{\beta} z^2 \Omega^2 P \left(\frac{2\pi N_2}{\lambda A_{\mathrm{eff}}}\right) \tag{2}$$

where m is the intensity modulation index, $\ddot{\beta} = -(\lambda^2/2\pi c) D$ is the second-order fiber dispersion coefficient, λ is the laser wavelength, D is the dispersion coefficient (ps/nm·km), z is the fiber length, N_2 is the Kerr nonlinear-index coefficient, and P is the injected optical power. Because the effective areas and dispersion parameters are $A_{\rm eff} = 72,\ 55$, and $80\,\mu{\rm m}^2$, and $D = 4,\ 5.2$, and 17 ps/nm·km for the LEAF, TWF, and SMF, respectively, from (2), we can expect that the second-harmonic distortion induced by LEAF is lower than that induced by SMF and TWF in externally modulated AM-SCM systems.

III. Experiments and Results

A. SBS Threshold

Three types of fiber media: corning LEAF, lucent TWF, and the conventional corning SMF are used in our experiments. The attenuation characteristics of these fibers are about the same with $\alpha = 0.2$ dB/km for the LEAF, TWF, and SMF. Fig. 1(a)–(c) shows the spontaneous Brillouin spectra of LEAF, TWF, and SMF measured at 1.55μm by using the ANDO AQ8602 Brillouin optical time-domain reflectometer (BOTDR). In Fig. 1(a), three large peaks and one small peak observed in the Brillouin spectrum of LEAF may be produced by the different composition or doping concentration in the core and high-order-longitudinal acoustic mode [8], and the relative powers are 77, 76, and 75.3 dB at Brillouin frequency shifts $\nu = 10.44,\ 10.83,\ 11.05$ GHz, respectively. From Fig. 1(b) and (c), the spectrum of either TWF or SMF has only one large peak, and the relative powers of the peaks are 84.35 and 80.04 dB at $\nu = 10.7$ and 10.84 GHz. If $g_{B,\,\rm LEAF}$, $g_{B,\,\rm TWF}$, and $g_{B,\,\rm SMF}$ are the maximal Brillouin gains for LEAF, TWF, and SMF, then the result of $g_{B,\,\rm LEAF} < g_{B,\,\rm SMF} < g_{B,\,\rm TWF}$ is observed from the spontaneous Brillouin spectra of LEAF, TWF, and SMF in Fig. 1(a)–(c). The effective areas are $A_{\rm eff} = 72,\ 55$, and $80\,\mu{\rm m}^2$ for the LEAF, TWF, and SMF, respectively. Therefore, the relationship of the SBS thresholds between LEAF, TWF, and SMF is $P_{t,\,\rm LEAF} > P_{t,\,\rm SMF} > P_{t,\,\rm TWF}$, where $P_{t,\,\rm LEAF}$, $P_{t,\,\rm SMF}$, and $P_{t,\,\rm TWF}$ are the SBS thresholds for LEAF, SMF, and TWF, respectively.

Fig. 2 shows the experimental setup for SBS threshold measurement. The commercial 1553.6-nm externally modulated distributed-feedback (DFB) laser transmitters (EM-TX), which increases the SBS threshold up to 17 dBm by using phase modulation and laser frequency dithering methods [9], is employed to carry AM-SCM signals. In CATV AM-VSB systems, the SBS threshold, at which the backscattered power slope increases rapidly with the fiber injected power (i.e., the "turning point" in the backscattered power curve versus fiber injected power), is considered as the more safe operating point than that of the classical definition for considering the CNR degradation caused by SBS according to [2]. The output signal of the EM-TX is amplified by an EDFA to 20.25 dBm. The optical power injected to fiber can be controlled by using the variable optical attenuator (VOA). In the experiments, the LEAF, TWF, and SMF, each with a length of 50 km, are separately placed between positions A and B. The optical power and CNR are measured by using power meter (PM) and an RF spectrum analyzer (SA). Fig. 3 shows the measured CNR at 55.25 MHz for the EM-TX operated with 3% modulation index and the received power without modulation as a function of fiber injected power for LEAF, TWF, and SMF. The SBS thresholds of LEAF, SMF, and TWF are 20, 17, and 13 dBm for the EM-TX with phase modulation and dithering operations. The SBS threshold is increased for the case using LEAF of about 3 and 7 dB as compared with the case using SMF and TWF, respectively.

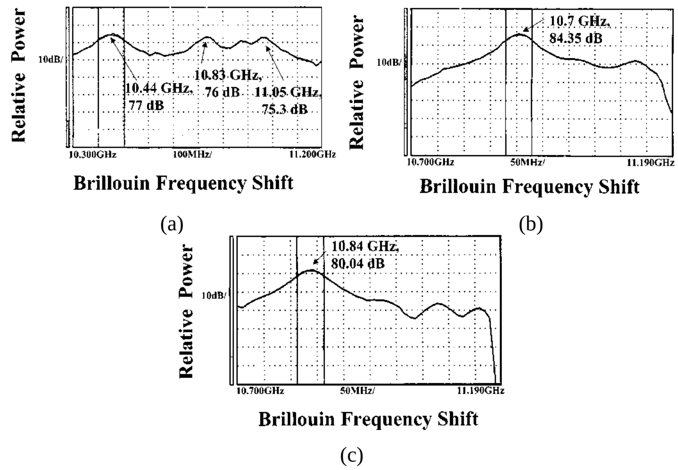

Fig. 1. The measured spontaneous Brillouin spectra of (a) LEAF, (b) TWF, and (c) SMF measured at 1.55 μm by using the Brillouin optical time-domain reflectometer (BOTDR).

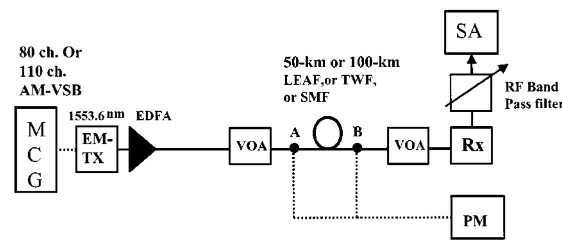

Fig. 2. Experimental setup.

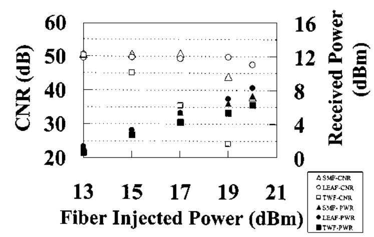

Fig. 3. The measured CNR at 55.25 MHz with 3% modulation index and the received power after passing fiber without modulation versus fiber injected powers for LEAF, TWF, and SMF in 1553.6-nm-EM transmission over 50 km fibers.

B. System Transmission

Without using the in-line optical amplifiers, the high power injected to fiber is required for long fiber span. For the comparison of the transmission performance between different fibers, a total of 110 CW carriers from the multicarrier generator (MCG), ranged from 55.25 to 745.25 MHz with 6-MHz spacing, are used to modulate the EM-TX with 3% modulation index over 50 km LEAF, TWF, and SMF, respectively. Fig. 4 shows the measured CNR and CSO distortion as .a function of fiber injected power for LEAF, TWF, and SMF. The power injected to fiber

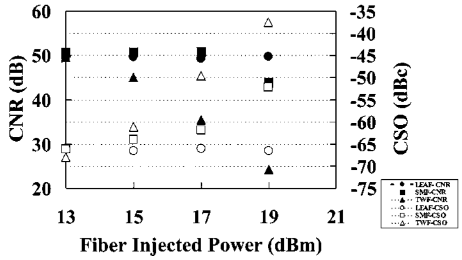

Fig. 4. Measured CNR and CSO distortion versus fiber injected power over 50-km of LEAF, TWF, and SMF for 1553.6-nm 110-channel AM-SCM transmission at 3% modulation index.

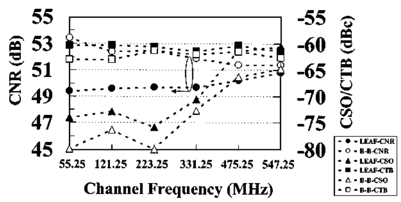

Fig. 5. Measured CNR, CSO, and CTB versus channel frequencies over 100-km LEAF for 1553.6-nm 80-channel AM-SCM transmission at 3.8% modulation index.

for LEAF, TWF, and SMF are ranged from 13–19 dBm, and the received powers at the AM receiver (Rx) are all kept at 0 dBm by controlling the VOA. In the high-power regime (>17 dBm), CNR and CSO performance of the LEAF system are superior to that of TWF and SMF systems. Therefore, the LEAF is more suitable than TWF and SMF for long distance transmission in AM-VSB systems.

We then measured the performance of the EM-TX carrying 80-channel at 3.8% modulation index, ranged from 55.25 to 545.25 MHz with 6-MHz spacing, over 100-km LEAF. The fiber-injected power is 19 dBm, and the received power of AM receiver is -1.7 dBm. As can be seen in Fig. 5, the system performance is $\mathrm{CNR} \geq 49.4$ dB, $\mathrm{CSO} \leq -60.5$ dBc, and composite-triple-beat (CTB) ≤ -60.3 dBc. Compared with the back-to-back performance, which is measured when EDFA output is connected with the AM receiver via a VOA and a fiber jumper by keeping the 0 dBm received power, the system performance over 100-km LEAF is degraded less than 4, 5.9, and 2.6 dB for CNR, CSO, and CTB. However, the system performance over 100-km LEAF meets the requirement of AM-VSB CATV systems.

IV. Conclusion

We have investigated the SBS threshold and transport of AM-SCM signal over LEAF, TWF, and SMF with external modulation. The transmission performance of $\mathrm{CNR} \geq 49.4$ dB, $\mathrm{CSO} \leq -60.5$ dB, and $\mathrm{CTB} \leq -60.3$ dB has been achieved for 80-channel AM-SCM transmission, which employed externally modulated DFB laser transmitter with phase modulation and frequency dithering, over 100-km LEAF without in-line optical amplifiers.

Acknowledgment

The authors would like to thank Dr. Y. K. Tu for his encouragement, and I. L. Yang and Dr. Y. K. Chen for their useful discussions and technical assistance.

References

[1] A. R. Chraplyvy, "Limitations on lightwave communications imposed by optical-fiber nonlinearities," *J. Lightwave Technol.*, vol. 8, pp. 1548–1557, 1990.

[2] X. P. Mao, G. E. Bodeep, R. W. Tkach, A. R. Chraplyvy, T. E. Darcie, and R. M. Derosier, "Brillouin scattering in externally modulated lightwave AM-VSB CATV transmission systems," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 287–289, 1992.

[3] H. Yoshinaga, "Influence of stimulated Brillouin scattering on nonlinear distortion in SCM video transmission," *Electron. Lett.*, vol. 29, pp. 1707–1708, 1993.

[4] 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. 7, pp. 481–483, 1991.

[5] O. Audouin and J.-P. Hamaide, "Enhancement of amplifier spacing in long-haul optical links through the use of large-effective-area transmission fiber," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 1363–1365, 1995.

[6] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995, pp. 370–378.

[7] P. Nouchi, P. Sansonetti, S. Landais, G. Barre, C. Brenm, J. Y. Boniort, B. Prttin, J. J. Griard, and J. Auge, "Low-loss single-mode fiber with high nonlinear effective area," in *Digest OFC'95*, 1995, ThH2.

[8] N. Shibata, K. Okamoto, and Y. Azuma, "Longitudinal acoustic modes and Brillouin-gain spectra for GeO_2-doped-core single-mode fibers," *J. Opt. Soc. Amer. B*, vol. 6, pp. 1167–1174, 1989.

[9] F. W. Willems, W. Muys, and J. S. Leong, "Simultaneous suppression of stimulated Brillouin scattering and interferometric noise in externally modulated lightwave AM-SCM systems," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1476–1478, 1994.