Hybrid 10-Gb/s, 2.5-Gb/s, 64-QAM, and AM-VSB High-Capacity Wavelength-Division-Multiplexing Transport Systems Using SMF and LEAF Fibers

Chien-Chung Lee, Yung-Kuang Chen, *Member, IEEE*, Chia-Hsiung Chang, Kai-Ming Feng, *Member, IEEE*, Sohn-Ling Tzeng, and Sien Chi

***Abstract*—A four-wavelength high-capacity hybrid wavelength-division-multiplexing (WDM) system separately over 100-km standard single-mode fiber and nonzero dispersion-shifted fiber of large effective area fiber is demonstrated. The WDM wavelengths contain one 10-Gb/s signal, one 2.5-Gb/s signal, one 64-quadrature amplitude modulator signal of 110 channels, and one amplitude module with vestigial sideband signal of 80 channels. Satisfaction of a huge variety of receiving requirements and reduction of fiber nonlinearities-induced degradations by controlling channel powers are also considered. Such a hybrid WDM system would be attractive for multiservice trunk applications in advanced transport systems for providing both CATV and telecommunication services.**

***Index Terms*—Hybrid wavelength-division multiplexing, large effective area fiber, video trunking, wavelength-division multiplexing.**

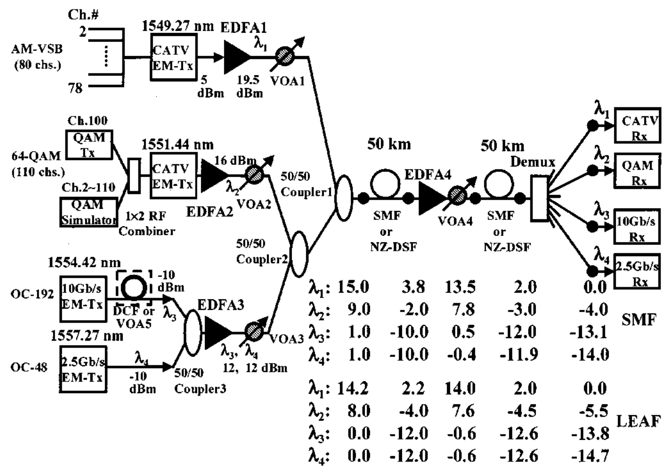

Fig. 1. Experimental setup of the hybrid WDM system.

I. Introduction

HIGH-DENSITY wavelength-division-multiplexing (WDM) system can fully utilize the optical fiber bandwidth and increase the capacity of a fiber link. A hybrid WDM system carries signals by its individual wavelength, and provides its flexibility in utilizing the vast bandwidth offered by an optical fiber for today's multimedia transport applications [1], [2]. Hybrid WDM systems with heterogeneous traffic is a natural choice to distribute both analog subcarrier multiplexing (SCM) signals and baseband digital signals simultaneously. There are several hybrid WDM systems explored previously with amplitude module with vestigial sideband (AM-VSB) and OC-48 [1] and FM-TV and OC-12 [2]. In addition, hybrid AM-VSB/M-QAM SCM multichannel video transmission through a single-wavelength transmitter has been studied [5]. However, hybrid WDM system with heterogeneous traffic of OC-48, OC-192, QAM, and AM-VSB has not yet been reported.

This work demonstrates a four-wavelength hybrid WDM system which transmits one OC-192 (10 Gb/s) signal, one OC-48 (2.5 Gb/s) signal, one 64-QAM of 110 channels, and one AM-VSB of 80 channels over 100-km fiber link of either standard single-mode fiber (SMF) or nonzero dispersion-shifted fiber of large effective area fiber (LEAF). Satisfaction of huge variety of receiving requirements and reduction of fiber nonlinearities-induced system degradations [4]–[6] by controlling channel powers are considered. Various system performances are examined and compared for different fiber media.

II. Experimental Setup

Fig. 1 shows the experimental setup of the hybrid WDM system with a link length of 100 km. The operating wavelengths of four externally modulated transmitters (EM-Txs) were at 1549.27 (λ_1), 1551.44 (λ_2), 1554.42 (λ_3), and 1557.27 (λ_4) nm for the AM-VSB, 64-QAM, OC-192, and OC-48, respectively. The channel spacing is about 2.2 nm between λ_1 and λ_2, about 3.0 nm between λ_2 and λ_3 channels, and about 2.9 nm between λ_3 and λ_4 channels. The AM EX-Tx was modulated by 80 NTSC RF channels (50–550 MHz) with an optical modulation index (OMI) of $\sim\ 3.2\%$. The 64-QAM testing signal at 651.25 MHz was generated from a Tektronix DVT200 QAM transmitter at 31.2 Mb/s, with 6-MHz bandwidth, and $2^{23}-1$ pseudorandom binary sequence (PRBS) data pattern. The rest of the 109 channels of 64-QAM signals were simulated by a QAM simulator, which consists of a programmable noise

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C.-C. Lee is with the Chunghwa Telecom Laboratories, Hsinchu 300, Taiwan, R.O.C. (e-mail: chchl@ms6.hinet.net) and also with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: chchl@ms6.hinet.net).

Y.-K. Chen and C.-H. Chang are with the Institute of Electro-Optical Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan, R.O.C.

K.-M. Feng and S.-L. Tzeng are with the Chunghwa Telecom Labs., Hsinchu 300, Taiwan, R.O.C.

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

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generator, a 750-MHz low-pass filter, and a notch filter with stopband of 648.25–654.25 MHz. A total of 110 64-QAM channels (50–750 MHz) was fed into an EM-Tx with an OMI of ~2.4%. The OC-192 EM-Tx was modulated by a 9.9533 Gb/s $2^{31}-1$ PRBS data. The OC-48 EM-Tx was modulated by a 2.488-Gb/s $2^{31}-1$ PRBS data. The extinction ratios of the 10- and 2.5-Gb/s signals were about 11 and >25 dB, respectively.

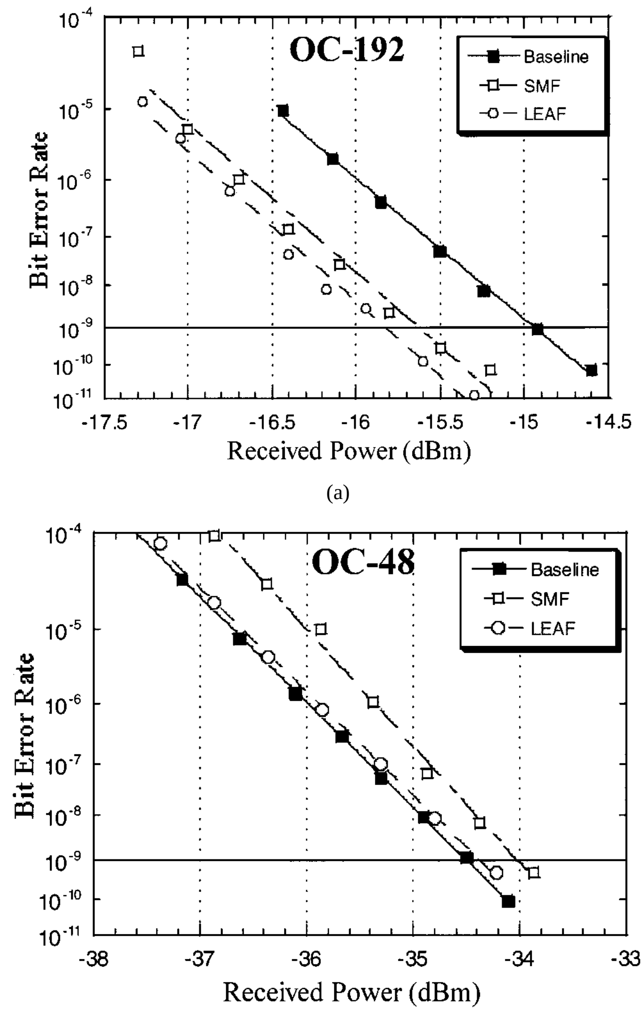
A dispersion-compensating fiber (DCF) module with a fiber length, total dispersion, and insertion loss of about 15-km, −1360 ps/nm, and ~ 6.4 dB, respectively, was used to pre-compensate the 100-km SMF link for the OC-192 channel. A variable optical attenuator (VOA) of 6.4 dB was used to replace the DCF module when the system operated with LEAF link. Three 980-nm-pumped EDFAs (EDFA1, 2, and 3) with the noise figures of 4.3–5.0 dB were used to boost these four wavelength channels to power levels of about 19 (λ_1), 16 (λ_2), 12 (λ_3), and 12 (λ_4) dBm, respectively. The system link includes two fiber spans (50 + 50 km) of either SMF or LEAF, and a 980-nm-pumped amplifier (EDFA4). The attenuation, dispersion, and effective core area of SMF and LEAF at 1550 nm are about 0.22 dB/km, 17 ps/km/nm, 80 μm^2, and 0.24 dB/km, 4 ps/km/nm, 72 μm^2, respectively. The output power and noise figure characteristics of EDFA4 are ~20 dBm and ~5.6 dB.

The controlled optical power levels of other WDM channels at each location (indicated with the "•" sign) for both SMF and LEAF links are also shown in Fig. 1. The high input power level is required to achieve a high carrier-to-noise ratio (CNR) for the AM-VSB channel, but it should not be too high to induce the harmful self-phase modulation and stimulated Brillouin scattering effects. Therefore, we set the AM-VSB input power level of each fiber span with ≤15 dBm, and with ≤14 dBm for the SMF and LEAF systems, respectively. Note that the power levels of the OC-192 and OC-48 digital baseband channels are about 14 dB lower than the AM-VSB channel, so that the digital channels have only a small effect on the EDFA4 gain. In addition, the power level of the QAM channel is set at about 6 dB lower than the AM-VSB channel in order to relax the co-existed cross-phase modulation (XPM) and stimulated Raman scattering (SRS) effects [6] between these two SCM channels with such narrow 2.2-nm channel spacing in both SMF and LEAF systems.

At the receiver end, a 1×8 WDM demultiplexer (Demux.) was used to demultiplex these four channels. The Demux is a thin-film coating-based device with a channel spacing of 200 GHz (1.6 nm), a passband width of ≈0.8 nm, an adjacent channel isolation of ≈40 dB, a nonadjacent channel isolation of ≈65 dB, and an insertion loss of 1–2 dB.

III. Experimental Results

For digital baseband channel performances, Fig. 2 shows the BER of the (a) OC-192 and (b) OC-48 channels for the 100-km WDM links using SMF and LEAF. For the OC-192 channel, the sensitivity at $\mathrm{BER} = 10^{-9}$ of the SMF and LEAF systems is −15.6 and −15.8 dBm, respectively. The corresponding sensitivity improvement is about 0.7 and 0.9 dB as compared with the baseline case. The improvement is attributed to the combination



(a)

(b)

Fig. 2. BER of the (a) OC-192 and (b) OC-48 channels.

of low accumulated link dispersion and the prechirped external modulator. The low accumulated dispersion is achieved by pre-compensation using DCF for the SMF link and low dispersion characteristics of the LEAF link. For OC-48 channel, the sensitivity at $\mathrm{BER} = 10^{-9}$ of the SMF and LEAF systems are −34 and −34.2 dBm, respectively. The corresponding power penalty after 100-km transmission is about 0.5 and 0.3 dB.

For AM-VSB performance, Fig. 3 shows the measured CNR, CSO, and CTB of the AM channels after 100-km transmission. Back-to-back (B-B) performance is also shown for comparison. In B-B case, the fiber link and EDFA4 were excluded. The CNR, CSO, and CTB of the frequency channel 78 at 547.3 MHz were about 47.7 dB, 71 dBc, and 66 dBc, respectively, for the SMF system, and about 47.8 dB, 73 dBc, and 71 dBc, respectively, for the LEAF system. The corresponding degradations of CNR, CSO, and CTB as compared with the B-B case were about 4.3, 2, and 5 dB, respectively, for the SMF system, and about 4.2, 0, and 0 dB, respectively, for the LEAF system. These CNR degradations are attributed to the SRS-induced power depletion of the AM channel to the OC-48 channel, and the fairly high noise figure (~5.6 dB) of the used EDFA4. For the low-frequency AM-VSB channels (55.25-223.25 MHz), the CNR of 100-km LEAF system was further degraded with a quantity of 1–2 dB,

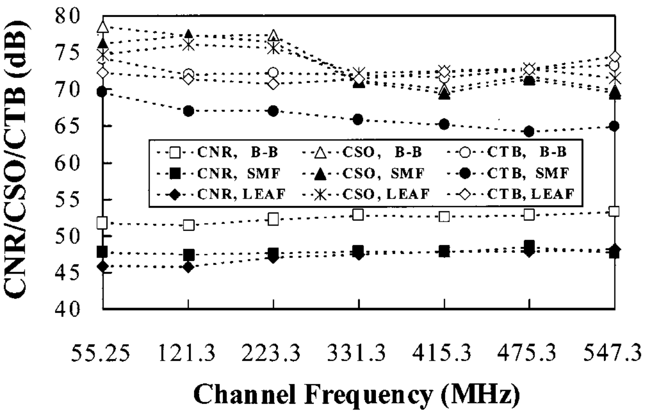


Fig. 3. Measured CNR, CSO, and CTB performances of the AM-VSB channels.

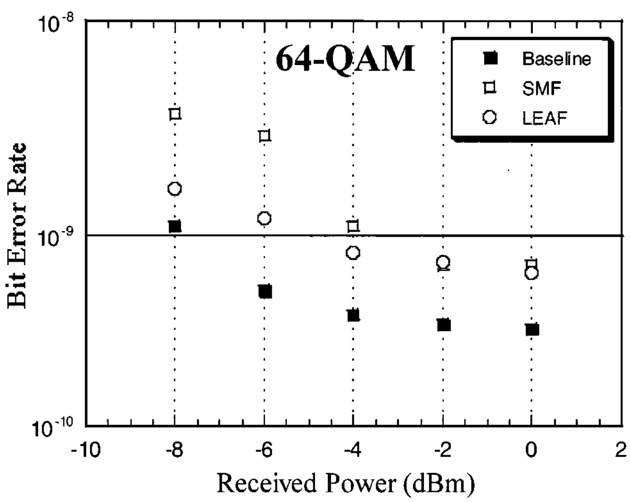


Fig. 4. BER of the 64-QAM testing channel.

which was induced by the SRS interaction between AM-VSB and OC-48 channel. This is because the OC-48 and AM-VSB channel pair with a channel separation of 8.5 nm suffered from the stronger SRS gain and interaction than that of the OC-192 and AM-VSB channel pair. This SRS interaction-induced CNR degradation was not observed in the 100-km SMF system and only occurred in the LEAF link, which was arisen from the small walkoff (i.e., less group velocity mismatch between the AM-VSB and OC-48 channels) effect in low dispersion region of the used LEAF.

Fig. 4 shows the BER of the 64-QAM testing channel. For a BER of 1×10^{-9}, the received signal powers of the SMF and LEAF systems are about -5 and -3 dBm, respectively. The corresponding power penalty is about 4 and 2 dB as compared with the baseline performance. For all cases, there exist some error floors. In baseline case (i.e., the fiber link and EDFA were excluded), the baseline floor was due to the limited performance of the QAM transmitter and demodulator pair. The power penalty of both SMF and LEAF systems were due to the signal spontaneous beat noise, which was enhanced by EDFA4. Although the power penalty seems to be intolerable, the 10^{-9} BER can be achieved in both systems with received signal power of ≥ 4 dBm. These CNR/CSO/CTB qualities of the AM-VSB channel, and the BER performances of the 64-QAM, OC-48, and OC-192 digital baseband channels in both SMF and LEAF systems all satisfy the transport system requirements. In addition, the optical channel assignment of this hybrid WDM system is not yet optimized due to the source restriction of the transmitter wavelength. In realization of a practical hybrid WDM system, the AM-VSB optical channel should be placed at the longest wavelength to minimize the SRS impact on other optical channels, then the channel power control can be relaxed and the power penalty of other optical channels can be further improved.

IV. Conclusion

We have demonstrated a four-wavelength externally modulated hybrid WDM system including one OC-48 signal, one OC-192 signal, one AM-VSB signal of 80 channels, and one 64-QAM signal of 110 channels over 100-km of either SMF, or LEAF link. By properly controlling channel powers, satisfaction of huge variety of receiving requirements and reduction of fiber nonlinearities-induced system degradations have been achieved. Satisfied system performances of $\mathrm{CNR} \approx 48$ dB, $\mathrm{CSO} > 71$ dBc, and $\mathrm{CTB} > 66$ dBc for AM-VSB signals, and BER of $<10^{-9}$ for OC-48, OC-192, and 64-QAM signals have been obtained for either SMF or LEAF system. The LEAF system is superior to the SMF one in the aspects of no need of dispersion compensation for the OC-192 channel, better CSO/CTB quality for the AM-VSB channel at the expense of 1.7-dB CNR degradation for the lower frequency channels, and smaller power penalty for both OC-48 and OC-192 digital baseband channels and QAM channel. Such a hybrid WDM system would be attractive for multiservice trunk applications in advanced transport systems for providing both CATV and telecommunication services.

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