REPEATERLESS HYBRID CATV/16-QAM OFDM TRANSPORT SYSTEMS

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Abstract—A repeaterless hybrid CATV/16-quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) transport system employing half-split-band and remote light injection techniques is proposed and demonstrated. Over an 80-km SMF transmission without optical amplification, good performances of carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB) were obtained for CATV band; simultaneous high CNR and low bit error rate (BER) values were achieved for 16-QAM OFDM band. This architecture presents a feasible way to transmit both analog and digital video signals.

1. INTRODUCTION

Fiber optical CATV transport systems are deployed widely to provide broad bandwidth to subscribers. Comparing with analog wireless TV systems, it can accommodate more channels to satisfy subscriber's

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requirements [1, 2]. However, the channel numbers of fiber optical CATV systems have reached limitations. In order to increase more channels, quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) modulation technique is required to involve in systems. Hybrid CATV/QAM OFDM transport systems including analog and digital signals are attractive for access networks, since it can deliver not only analog CATV signals but also multiple numbers of digital ones. As a result, the channel numbers of fiber optical CATV systems can be increased significantly. Hybrid CATV/QAM OFDM architecture is, therefore, considered as a promising candidate to transmit both analog and digital signals simultaneously. The feasibility of simultaneously transmitting both analog with 6-MHz bandwidth and digital signals at specific data rate in a hybrid transport system was demonstrated previously [3, 4]. Nevertheless, system's performances can be further improved by employing half-split-band and remote light injection techniques [5, 6]. In this paper, a repeaterless hybrid CATV/16-QAM OFDM transport system based on half-split-band and remote light injection techniques is proposed and demonstrated. Half-split-band technique, dividing signals into low-band and high-band ones and resulting in removing the distortions of systems automatically and greatly, is expected to have good performance in hybrid CATV/16-QAM OFDM transport systems. In addition, remote light injection technique is a performance improvement scheme for hybrid CATV/16-QAM OFDM transport systems due to the enhancement abilities of laser resonance frequency, frequency chirp, and relative intensity noise (RIN). Good performances of carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB) were obtained for CATV band, as well as high CNR and low bit error rate (BER) values were achieved for 16-QAM OFDM band over an 80-km single-mode fiber (SMF) transmission.

2. EXPERIMENTAL SETUP

The experimental configuration of our proposed repeaterless hybrid CATV/16-QAM OFDM transport systems employing half-split-band and remote light injection techniques is shown in Figure 1. A total of 121 carriers, from a multiple signal generator (Matrix SX-16) and a 16-QAM OFDM modulator, were used to simulate analog CATV channels (CH2-40) and 16-QAM digital TV ones (CH41-74 and 48 carriers from 16-QAM OFDM modulator). Each 16-QAM OFDM signal carrier carries a date rate of 28 Mbps, thus, the total of 48 carriers has the transmission capacity of 1.344 Gbps (28 Mbps/carrier × 48 carriers).

Channels 2-40 were directly fed into the distributed feedback (DFB) laser diode1 (LD1). Different from analog CATV signals, digital TV signals were represented by 34 simulated RF carriers (channels 41–74) and 48 16-QAM OFDM carriers (550.97–567.53 MHz, with a carrier separation of 312.5 kHz); both of the carriers were combined and directly fed into the DFB LD2. The central wavelengths of DFB LD1 and DFB LD2 are 1530.81 (λ_1) and 1531.94 nm (λ_2), respectively. The output power levels and RIN of these two DFB LDs are 17 dBm and −170 dB/Hz, respectively. Just above the analog carrier, the lower digital 16-QAM OFDM signals are seen.

The optical powers of the two DFB LDs were coupled into an 80-km SMF through a 2×1 optical coupler. As to the remote light injection part, light was injected through the 3-port optical circulators (OCs). The wavelengths of the injected light are 1530.90 (λ_1') and 1531.99 nm (λ_2'), respectively. They must be accurately chosen to ensure that the optimal enhancement in laser resonance frequency, frequency chirp, and RIN. The injection power level is 8 dBm per wavelength. For λ_1' (λ_2') to λ_1 (λ_2) injection-locked, λ_1' (λ_2') is coupled into the port1 of OC1 (OC2), the injection-locked λ_1 (λ_2) is coupled into the port2 of OC1 (OC2), and the port3 of OC1 (OC2) is launched into a 2×1 optical coupler. These 3-port OCs have excellent optical characteristics including low insertion loss ($\sim$0.8 dB) and high isolation (> 40 dB). Such high isolation ability prevents the reflected laser light
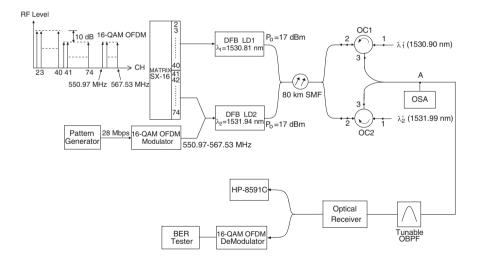

Figure 1. Experimental configuration of our proposed repeaterless hybrid CATV/16-QAM OFDM transport systems employing half-split-band and remote light injection techniques.

from getting into the injection light source. At point A, the spectra were measured by using an optical spectrum analyzer (OSA). After an 80-km SMF transmission, the optical signal was went through a tunable optical band-pass filter (OBPF) to select the appropriate wavelength, and detected by an optical receiver. The output of the optical receiver was separate off by a 1×2 RF splitter, then applied to an HP-8591C CATV analyzer and a 16-QAM OFDM demodulator. CNR, CSO and CTB values were measured using an HP-8591C CATV analyzer; and the 16-QAM OFDM channel was demodulated and fed into a BER tester for BER analysis.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

One key feature of injection locking is that the injected laser is forced to oscillate at the injection frequency instead of the original free-running frequency. Therefore, the frequency component at the injection frequency becomes dominant. The injection locking behavior happens when an injection laser (λ_1' and λ_2') is slightly detuned to frequency lower than that of the injected laser (λ_1 and λ_2); i.e., negative frequency detuning is employed to achieve an injection locking [7]. As λ_1 (λ_2) is injection-locked, its optical spectrum shifts a slightly longer wavelength to λ_1' (λ_2'). When an injection-locked LD with negative frequency detuning, its main mode is amplified, while the side modes are suppressed [8, 9]. In the free-running case, as shown in Figure 2(a), the side mode suppression ratio (SMSR) value is only >32 dB. While remote injection locking enhances the intensity of main mode, suppresses the intensities of side modes, and produces the optical spectrum as shown in Figure 2(b). It shows the optical spectrum of the injection locking DFB LD1 and DFB LD2 locked at λ_1' and λ_2', with a SMSR value >48 dB. The dynamics of injection locking behavior can be described by the following rate equations [10]:

$$\frac{dA(t)}{dt} = \frac{1}{2}g[N(t) - N_{th}]A(t) - kA_{inj}\cos\phi(t) \tag{1}$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2}g[N(t) - N_{th}] - k\frac{A_{inj}}{A(t)}\sin\phi(t) - 2\pi\Delta f \tag{2}$$

$$\frac{dN(t)}{dt} = J - \gamma_N N(t) - \{\gamma_p + g[N(t) - N_{th}]\}A^2(t) \tag{3}$$

where $A(t)$ is the field amplitude ($A^2(t) = S(t)$, $S(t)$ is the photon number), $\phi(t)$ is the phase difference between the temporal laser field of the slave laser and the master laser, $N(t)$ is the carrier number, g is the gain coefficient, N_{th} is the threshold carrier number, A_{inj}

is the field amplitude injected into the slave laser, k and α denote coupling coefficient between injected field and laser field, Δf is the lasing frequency difference between the master and the slave laser in the free-running state, J is the injection current, γ_N is the carrier decay rate, and γ_p is the photon decay rate. Remote light injection locking is achieved effectively due to the fact that the SMSR value is increased. The wavelength of the remote injected light must be carefully chosen to ensure that the maximum optical enhancement in SMSR is obtained. The optimal injection locking condition is found as the detuning between λ_1 and λ_1' is 0.09 nm, and between λ_2 and λ_2' is 0.05 nm.

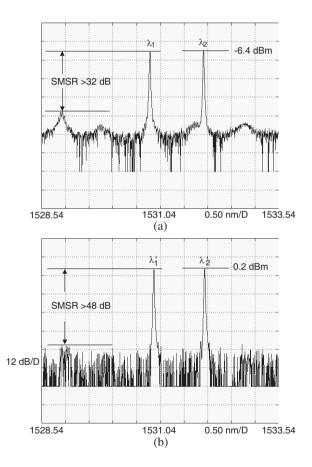**Figure 2.** The optical spectrum of (a) DFB LD1 and DFB LD2 under free-running, (b) the injection locking DFB LD1 and DFB LD2 locked at λ_1' and λ_2'.
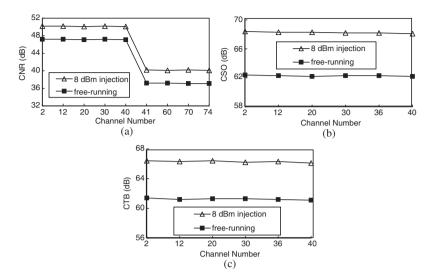
Figure 3. (a) Measured CNR values. (b) Measured CSO values. (c) Measured CTB values.

Figure 3(a) shows the measured CNR values under NTSC channel number (CH2-74) for free-running and with 8-dBm remote light injection, respectively. It indicates that the CNR values are increased as 8 dBm optical power is remotely injected. For a repeaterless long-haul lightwave transport system, CNR_{shot} (due to shot noise) term dominates the CNR value [11]:

$$CNR_{shot}^{-1} = \frac{4h\upsilon}{m^2 \eta c_1 P_{in} G L_f} \qquad (4)$$

where $h\nu$ is the photon energy, m is the optical modulation index, η is the corresponding ratio, c_1 is the input coupling loss, P_{in} is the input optical power of optical receiver, G is the gain of remote light injection scheme, and L_f is the loss factor between the remote light injection scheme and the optical receiver. It is clear that the CNR depends critically on the input optical power P_{in}. CNR_{shot} of systems with 8 dBm remote light injection is higher than that of systems in the free-running case, since higher optical power level is received by the optical receiver. The higher optical power level is received by the optical receiver, the higher CNR value is obtained in systems. With 8-dBm remote light injection, for simulated CATV signals transmission (CH2-40), the CNR value of >50 dB of systems satisfies the fiber optical CATV requirement. Also with 8-dBm remote light injection, for simulated 16-QAM OFDM signals transmission (CH41-74), the worst

CNR value is >40 dB. It meets the required 30 dB for the 16-QAM OFDM signals with BER $< 10^{-9}$. Moreover, the measured CNR values for simulated CATV signals are 10 dB higher than those for 16-QAM OFDM signals, since each of the simulated 16-QAM OFDM signals has their levels adjusted so they carry 10 dB below the simulated CATV signals.

As to the CSO/CTB performances, the CSO and CTB values of systems are shown in Figures 3(b) and (c), respectively. In the free-running case, the CSO/CTB values are limited around 62 and 61 dB, respectively. With 8-dBm remote light injection, however, these two values are improved significantly to 68 and 66 dB. The improvements are due to the use of the half-split-band and remote light injection techniques. CSO and CTB distortions are given by [12]:

$$CSO = 10 \log(N_{CSO}) + IMS_2 \qquad (5)$$

$$CTB = 10 \log(N_{CTB}) + IMS_3 + 6 \qquad (6)$$

where N_{CSO} and N_{CTB} are the product counts of CSO and CTB, IMS is the intermodulation suppression, and IMS_2 and IMS_3 are the ratios of second- and third-order coefficients to fundamental coefficients, respectively. By using half-split-band technique, smaller N_{CSO} and N_{CTB} can be obtained from smaller channel numbers; thereby, part of the CSO and CTB distortion are removed dramatically and automatically in each split-band region. IMS_2 and IMS_3 can be expressed as

$$IMS_2 \cong 10 \log \left\{ m \frac{(f/f_r)^2}{g(2f)} \right\} \qquad (7)$$

$$IMS_3 \cong 10 \log \left\{ \frac{m^2}{2} \frac{(f/f_r)^4 - \frac{1}{2}(f/f_r)^2}{g(f)g(2f)} \right\} \qquad (8)$$

where f_r is the laser resonance frequency, and $g(f)$ is the gain of the laser medium as a function of frequency. From Equations (7) and (8), it is obvious that both IMS_2 and IMS_3 can be very small as f_r is very large. The use of remote light injection technique increases laser resonance frequency, resulting in system with lower IMS_2 and IMS_3, and leading to an improvement of CSO and CTB performances.

The measured BER curves as a function of the received optical power level for free-running and with 8 dBm remote injection are presented in Figure 4. For free-running and at a BER of 10^{-9}, the received optical power level is -15.4 dBm. Nevertheless, this value is reduced to -20.2 dBm as the remote light injection source is injected. Comparing to the free-running case, 4.8 dB improvement
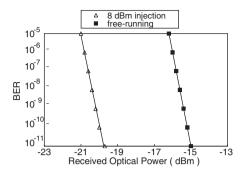
Figure 4. Measured BER curves as a function of the received optical power level.

of the received optical power level is achieved. Large BER performance improvement is the result of using remote light injection technique to reduce the RF power degradation [13].

4. CONCLUSION

A repeaterless hybrid CATV/16-QAM OFDM transport system based on half-split-band and remote light injection techniques is proposed and demonstrated. Over an 80-km SMF transmission without optical amplification, impressive performances of CNR, CSO and CTB were obtained for CATV band; simultaneously remarkable BER improvement had been achieved for 16-QAM OFDM band. These prominent results verify the potential of the proposed systems to integrate both CATV and 16-QAM OFDM signals.

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