740-km Transmission of 78-Channel 64-QAM Signals (2.34 Gb/s) Without Dispersion Compensation Using a Recirculating Loop

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***Abstract*—A long-distance 1550-nm subcarrier multiplexed lightwave trunk system that transported 78 channels of 64-QAM signals was demonstrated in a recirculating loop experiment. Each channel can achieve a carrier-to-(noise + nonlinear distortion) ratio of 30 dB after 740-km transmission through conventional single-mode fiber without dispersion compensation.**

***Index Terms*—Cable TV, hybrid fiber coax, optical fiber communication, QAM, subcarrier multiplexing.**

I. Introduction

A SUBCARRIER multiplexed (SCM) lightwave system transporting multichannel M-ary quadrature-amplitude-modulation (M-QAM) signals can have transmission features such as high system capacity and long transmission distance [1]–[3]. This is due to the fact that the carrier-to-noise ratio (CNR) and carrier-to-nonlinear distortion ratio (CNLD) requirements of M-QAM signals are lower than those of AM-VSB signals. In addition, M-QAM signals have a high spectral efficiency, which makes multigigabit/s data transmission feasible when using conventional CATV optical transceivers. Therefore, multichannel M-QAM SCM trunk systems have a great potential to be used for interconnecting CATV headends and delivering various digital communication services. It was found that the fundamental M-QAM system capacity of either a laser diode- or a linearized external modulator-based transmitter could be as high as tens of gigabits/s [4], [5]. However, the transmission distances of all reported M-QAM SCM systems are still rather limited. In this letter, we experimentally demonstrated that the transmission distance of an M-QAM external modulation SCM system carrying an equivalent data capacity of 2.34 Gb/s could exceed 740 km. In addition, for the first time, an optical fiber recirculating loop was implemented in an SCM system experiment.

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II. Experimental Setup

Our recirculating loop experimental setup is shown in Fig. 1. The transmitter was composed of a 20-mW, 1561.6-nm MQW-DFB laser with a linewidth of 1.4 MHz and a $LiNbO_3$ Mach–Zehnder (MZ) modulator. Two types of signal sources were used: 78 channels of CW tones generated from a multicarrier generator, or 78 channels of 64-QAM signals generated from a 2.6-Gsamples/s, 8-bit/sample arbitrary waveform generator. In both cases, the 78 channels of signals ranged from 54–552 MHz with an rms OMI/ch given by 3.2%. For the case of CW tones, the worst case back-to-back (optical transmitter to receiver) CSO and CTB were 55 dB and 47 dB, respectively. For the case of 64-QAM signals, the back-to-back signal-to-noise ratio (SNR) per channel was about 34.5 dB. For each of the 64-QAM channels, 4096 5-Ms/s random baseband pulse-amplitude-modulation symbols with eight levels were generated. After the constellation mapping, the symbols were split into I and Q channels. The I and Q channels were then band-limited by root-raised-cosine filters with $\alpha = 0.2$. The filtered baseband waveforms were then quadrature modulated (with a random carrier phase) to the center frequency of a particular channel [4]. A total of three EDFAs were used in the experiment. $EDFA_0$ was used as a booster amplifier. $EDFA_1$ and $EDFA_2$ were used as in-line amplifiers. The noise figures of the in-line EDFAs were about 5 dB. Three spans of conventional single mode fiber (SMF) with lengths of 40.6 km, 47.8 km, and 48.5 km were used in the setup. The fiber loss and effective core area were measured to be 0.2 dB/km and 90 μm^2, respectively. The total fiber length per loop was 96.3 km. To avoid a fiber-dispersion-induced carrier compression effect [6], no external phase modulation was used. Therefore, the output power levels of each EDFA were maintained at $+6$ dBm. The input power levels to each in-line EDFA were adjusted to be -4 dBm. The loop gain and loss were carefully balanced, and this power balance was constantly monitored by coupling 1% optical power from the loop to a photodiode, as shown in Fig. 1(b). Three acousto-optic modulators (AOMs) with 50-dB extinction ratio were used as the controlling switches to circulate the modulated light in the loop. As shown in Fig. 1(a), each cycle of the control signal was composed of a “load” state, followed by M “loop” states, where M depends on the number of recirculation. The duration of the load state was adjusted to be $\sim 474\ \mu s$, which is the time that the modulated light needed to travel through the 96.3-km loop [see Fig. 1(a)]. When AOM_0 and AOM_1 were ON (AOM_2 was OFF), modulated light from

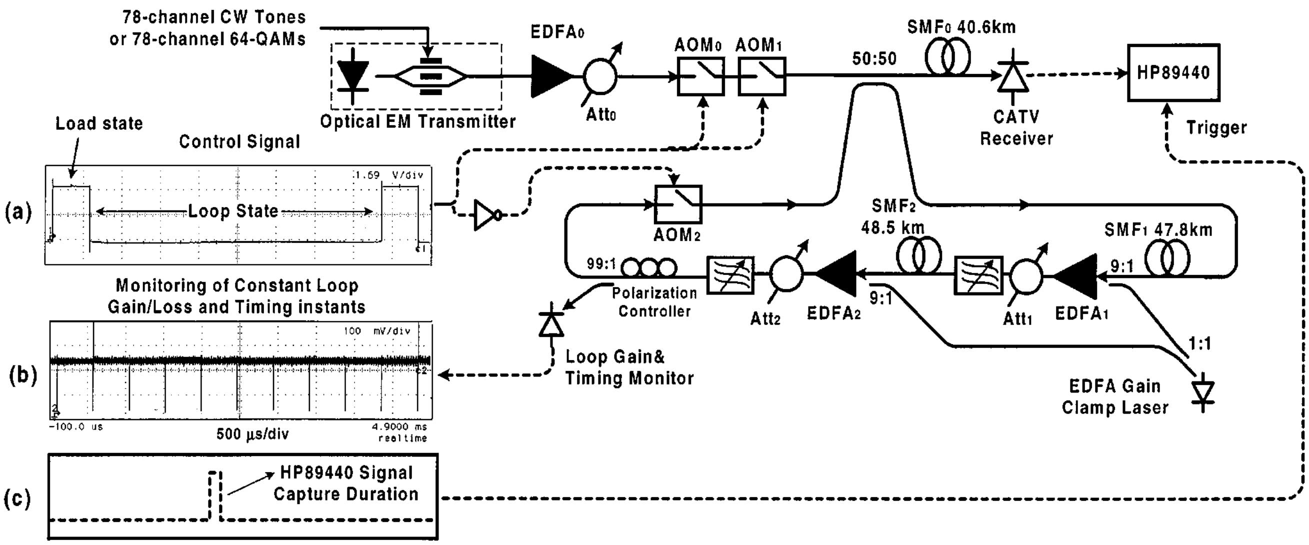

Fig. 1. Experimental setup of an SCM recirculating loop.

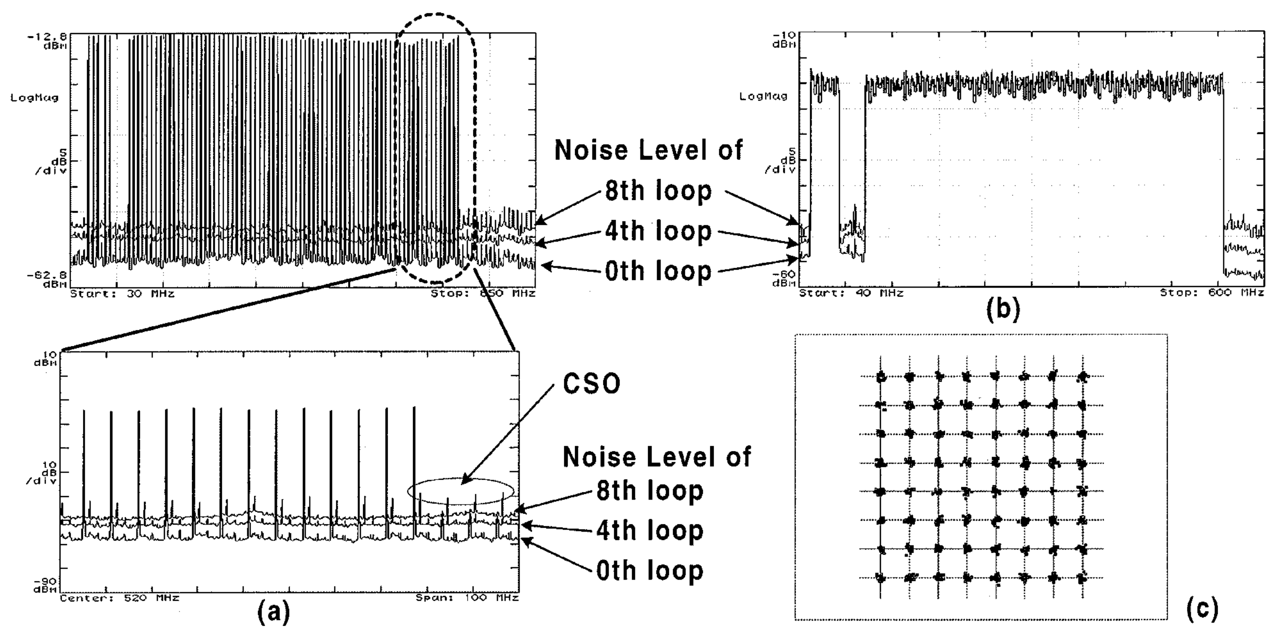

Fig. 2. Captured 78-channel CW tones (a) and 64-QAM signals (b) after 0, 4, 8 times of recirculating loops. (c) is the measured 64-QAM signal constellation diagram of channel 78 after seven times of the recirculating loop (714 km).

the optical transmitter was fed into the loop. Following the load state were M loop states, which were used to turn AOM_0 and AOM_1 off to block the signal from transmitting into the loop, and to turn AOM_2 on so as to enable signal recirculating M times in the loop. A gain-clamped laser was used to suppress the gain transients occurring in the in-line EDFAs.

The Received signal was analyzed on a vector signal analyzer (HP89440), whose triggering time for FFT spectrum display can be controlled. The signal capture duration of the signal analyzer was set to be 66.7 μs, as shown in Fig. 1(c). The triggering for the onset of capture time must be carefully controlled so that those transient instants shown in Fig. 1(b) would not be included. The resolution bandwidth corresponding to the 66.7 μs signal capture time was 57.3 kHz. $C/(NLD+N)$ per channel (6 MHz) was measured by using the band power measurement function of the vector signal analyzer.

III. Results and Discussion

The measured signal spectra of the received 78-channel CW tones and 78 channels of 64-QAM signals after three looping transmission distances (40, 425, and 810 km) are shown in Fig. 2(a) and (b), respectively. We can clearly see the growth of the self-phase modulation (SPM)-induced composite second-order (CSO) distortions, and the growth of total noise levels, as the transmission distance was increased. Fig. 2(c) shows the measured 64-QAM signal constellation diagram of channel 78 after transmission through seven times of recirculating loop (714 km).

In the case of transmitting 78 channels of CW tones, the measured and calculated results of CSO and CNR as functions of transmission distance are shown in Fig. 3(a). For all transmission distances, the worst case CSO occurred at channel 78,

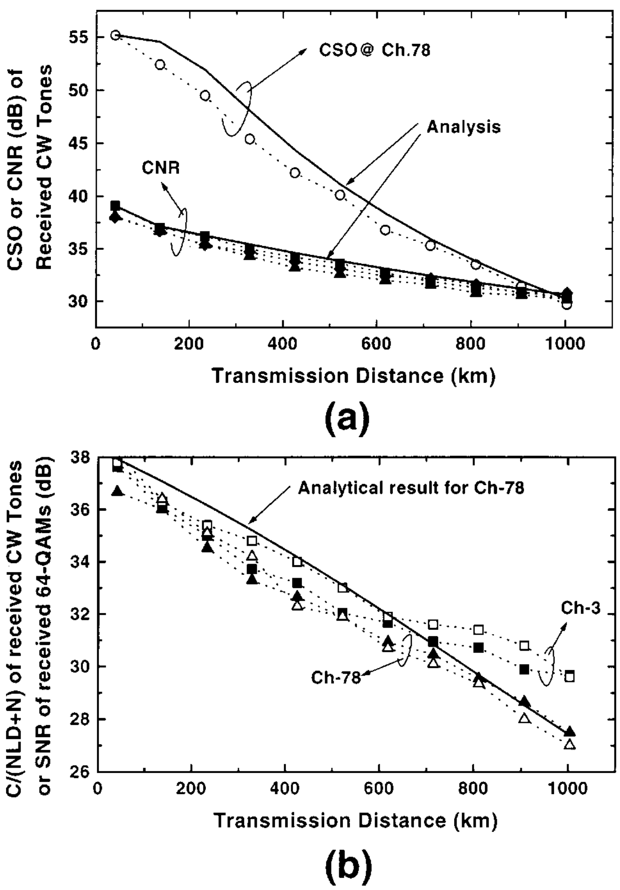

Fig. 3. (a) Measured CNR of Ch.3 (♦), Ch.39 (■), and Ch.78 (▲) in a 6-MHz bandwidth, and the worst case CSO at Ch.78 (○), for the case of transmitting 78 CW tones. (b) Measured $C/(NLD + N)$ of Ch.3 (□) and Ch.78 (△) when transmitting 78 CW tones, and the measured SNR of Ch.3 (■) and Ch.78 (▲) when transmitting 78 64-QAM signals. Solid lines in (a) and (b) are the calculated results. Launched optical power was $+6$ dBm.

and the measured results are shown in open circles. The corresponding calculated CSOs (solid line) were obtained by adding the back-to-back CSOs with those from the SPM analysis [7]. The deviation between calculated and measured CSOs is within 2 dB. Also shown in the figure are the measured CNRs for channels 3, 39, and 78, and the calculated CNRs for channel 78. The noise terms in these calculated CNRs include EDFA signal-spontaneous beat noise and the fiber dispersion-induced phase-to-intensity conversion noise [8]. The deviation between calculated and measured noise was mainly due to the insufficient extinction ratios of the AOMs and the AOM acousto-optic frequency shift-induced beat noise in the loop experiment.

Fig. 3(b) is used to compare the measured $C/(NLD + N)$ obtained from 78 CW-tones with the measured SNRs from 78 64-QAM signals (for channels 3 and 78, respectively). Note that, for the case of CW tones, the measured $(NLD + N)$ have included all order of nonlinear distortion and noise in a 6-MHz band; while for the case of 64-QAM signals, the measured SNR was estimated by digital demodulation function of the vector signal analyzer. In addition, the artificial background noise from the AWS has been calibrated out. We can clearly see that the differences between $C/(NLD + N)$ for tones and SNR for 64-QAM signals were within 1 dB, as has also been rigorously confirmed in [9]. According to the measured results shown in Fig. 3(b), we can see that for a $C/(NLD + N) \geq 30$ dB (required for a 64-QAM without forward-error-correction to achieve a BER of 10^{-9}), the transmission distance can be as long as ~740 km. Also shown in the figure is a solid line representing the calculated $C/(NLD + N)$ at channel 78 (the worst case channel) as a function of transmission distance, which was based on the calculated CSO and CNR results given in Fig. 3(a).

IV. Conclusion

By carrying out a recirculating loop experiment, we have demonstrated that 1550-nm CATV external modulation systems can be used to deliver 78 channels of 64-QAM signals (equivalent to a capacity of 2.34 Gb/s) over a transmission distance >740 km of conventional SMF without dispersion compensation. In addition, our analysis shows that, in such long-distance systems, the dominant system degradation factors include the SPM-induced second-order nonlinear distortions, the signal-spontaneous beat noise due to cascaded EDFAs, and the intensity noise converted from laser phase noise owing to the presence of significant optical fiber-dispersion.

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