An Optical Sampled Subcarrier Multiplexing Scheme for Nonlinear Distortion Reduction in Lightwave CATV Networks

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Abstract – **This paper proposes and demonstrates a nonlinear distortion reduction scheme for subcarrier multiplexed optical CATV networks based on optical sampling and optical time-division multiplexing (OTDM) techniques. Inter-modulation distortion is reduced by about 10 dB for a 40-channel system. The proposed optical sampling and OTDM process is shown to induce negligible additional distortion.**

I. INTRODUCTION

Optical subcarrier multiplexing (SCM) has been widely used for multi-channel analog video distribution [1] over optical fiber. It has also found applications in cellular networks [2] and even in high-speed data communications [3]. One of the major impairments in optical SCM system is the presence of intermodulation distortion (IMD) caused by the nonlinearity of various optical or electrical components in the whole system. Several IMD reduction approaches were previously proposed, which included improving the linearity of the optical components; using pre-distortion/feed-forward compensation techniques; or performing careful RF frequency planning. In this paper, we propose and demonstrate a new distortion reduction technique based on optical time-division multiplexing (OTDM) and optical sampling. By splitting the composite SCM carriers into two orthogonal TDM channels, IMD can be reduced substantially. The proposed multiplexing/demultiplexing process is shown to induce negligible additional distortion. Besides, the scheme does not require an additional wavelength or fiber. No frequency conversion is necessary.

II. OPTICAL SAMPLED SUBCARRIER MULTIPLEXING (OS-SCM)

Here, we propose a novel technique, called optical sampled subcarrier multiplexing technique (OS-SCM) to perform IMD reduction. Fig. 1 illustrates the principle of an OS-SCM system. It assembles the conventional SCM system except that an optical short pulse source, instead of a CW laser source, is used in external modulation. This short pulse source can be a gain-switched laser or mode-locked laser, which generates high repetition rate optical short pulses. Multiple RF subcarrier channels are multiplexed to form a composite signal, which is then used to intensity-modulate the optical short pulses. Thus, the intensity envelope of the optical pulse train carries the subcarrier composite signal. For a group of subcarriers having a maximum frequency of f_{max}, the repetition rate of the optical pulse train must be more than $2f_{max}$ in order to meet the Nyquist criterion. At the receiving end, a bandpass filter is used to filter out the desired RF subcarrier channel.

Theoretically, a sampled analog system (like pulse amplitude modulation (PAM)) possesses no performance advantage over amplitude modulated CW system in terms of the signal-to-noise ratio of the received signal [8]. There are, however, advantages when sampling is applied on an optical SCM system. For example, a recent study [4] showed that optical sampling could increase the stimulated Brillouin scattering (SBS) threshold of fiber, thus allowing more power to be launched into optical fiber for transmission. As a result, carrier-to-noise ratio (CNR) of the received signal could be improved. In this paper, we demonstrate that our proposed OS-SCM scheme can be employed to achieve nonlinear distortion reduction.

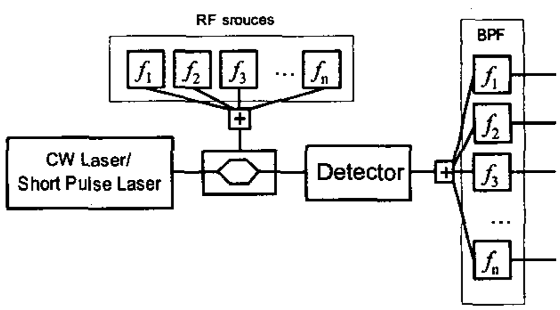

Fig. 1 AM CW and OS-SCM transmission system

III. PROPOSED DISTORTION REDUCTION SCHEME

Among all the nonlinear distortions, third-order IMD is the most difficult to tackle as it lies within the SCM channel frequency band. It has been shown that the number of third

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order IMD is proportional to N^2 for an N-channel SCM system [5]. Thus an intuitive method to reduce the IMD is to off-load some of the subcarrier channels to additional wavelength or fiber links. However, this method inevitably requires extra system bandwidth, which could otherwise be used to deliver other services.

In view of this, we propose another way to off-load subcarrier channels without using additional wavelength or fiber resources. This is achieved using optical sampling and OTDM technique. The principle is to create a number of time-domain channels within one single wavelength. Subcarrier frequencies are then distributed over these time domain channels. If the isolation between adjacent time-domain channels is sufficient, the number of RF channels contributing to IMD in each TDM channel can be reduced and hence the intensity of IMD can also be reduced.

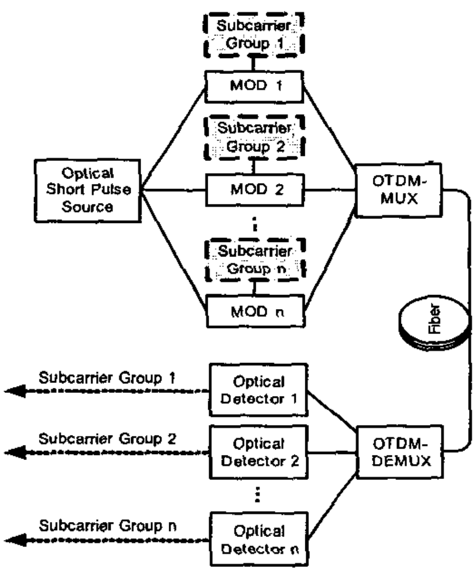

Fig. 2 Nonlinear distortion reduction scheme using OS-SCM and OTDM

The proposed nonlinear distortion reduction scheme is illustrated in Fig. 2. An optical short pulse source is used to generate high repetition rate optical pulse train, which acts as the carrier for subcarrier signals. Subcarrier channels to be transmitted are divided into several groups. Assignment of frequencies in each group can follow a fixed-frequency-spacing approach. Alternatively, specialized algorithms previously implemented in [6, 7] can also be employed. These algorithms can yield further distortion reduction when compared with fixed spacing approach. Each frequency group is then used separately to modulate an optical pulse train by an external modulator.

An OTDM multiplexer is used to 'bit-interleave' these modulated pulse trains together. At the receiving end, an OTDM demultiplexer is used to separate the interleaved pulse trains, each of which is then detected by an optical detector.

Ideally, there are no intermodulations generated among different groups of frequencies due to the use of OTDM technique. In actual implementation, care should be taken to select appropriate pulse source and OTDM demultiplexer. Pulses sources having low extinction ratio are undesirable as multiplexing of such pulse train would result in optical beat interference (OBI) among OTDM channels during the interleaving process. The optical pulses also need to be sufficiently short to avoid inter-channel interference. Similarly, the OTDM demultiplexer at the receiving end should also have a high extinction ratio and narrow switching window in order to provide a high degree of isolation between adjacent time channels.

IV. EXPERIMENTAL INVESTIGATION

The experimental setups for investigating the performance of the proposed nonlinear distortion reduction scheme are illustrated in Fig. 3 and Fig. 4.

We first measured the composite triple beat (CTB) value of a 40-channel SCM system using a CW laser and a mode-locked fiber ring laser as the source, respectively. These two baseline values are then compared with the CTB values obtained from the proposed nonlinear distortion reduction setup.

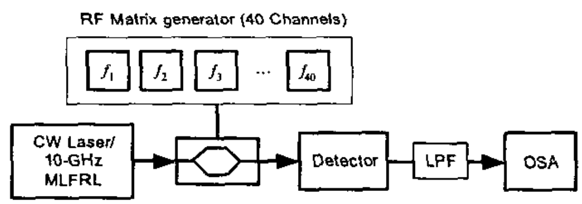

Fig. 3 CTB baseline measurement for CW AM and OS-SCM

Fig. 3 illustrates the experimental setup for a 40-channel SCM system without distortion reduction. A CW laser was first used as the source for subcarrier modulation. The modulator used in the experiments does not have pre-distortion compensation thus it was rather nonlinear. The modulation depth is around 5% per channel. This setup was used to obtain a reference CTB level. Trace (a) in Fig. 8 shows the measured CTB value of selected 20 out of the 40 channels.

We then attempted to characterize the system penalty due to

OS-SCM. This was done by replacing the CW laser source with a mode-locked fiber ring laser (MLFRL), which generated 10-GHz 3-ps optical pulses. After external modulation, the detected RF spectrum was captured, as depicted in Fig. 4. The measured CTB values were plotted in Fig. 8 as trace (b). It can be observed that the trace nearly overlaps with trace (a). This indicates the penalty of using high repetition rate optical pulse train as the source for SCM modulation is negligible.

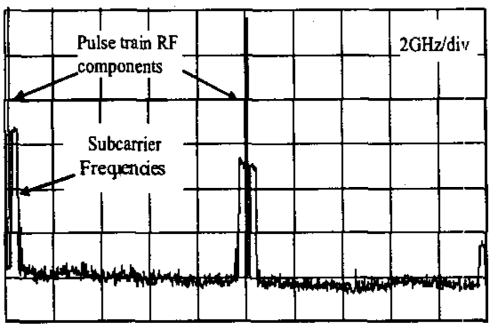

Fig. 4 RF spectrum of the pulse modulated subcarrier signals. Central Frequency = 10GHz.

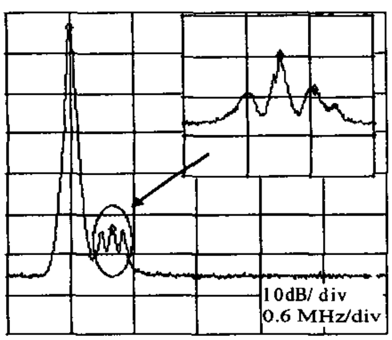

Fig. 5 MLFRL cavity mode spikes manifested as interference. Central Frequency = 122.45 MHz

Upon close inspection on individual RF channel, we observed some periodic frequency spikes as shown in Fig. 5 and Fig. 6. The power of these spikes was independent of the modulated RF signals. In fact, they were residual cavity modes generated by the long fiber cavity of MLFRL. Such frequency spikes could cause signal quality degradations. However, it was not an intrinsic degradation due to OS-SCM and they could be completely eliminated by replacing the MLFRL with other pulse sources, such as short-cavity mode-locked laser diodes or gain-switched lasers.

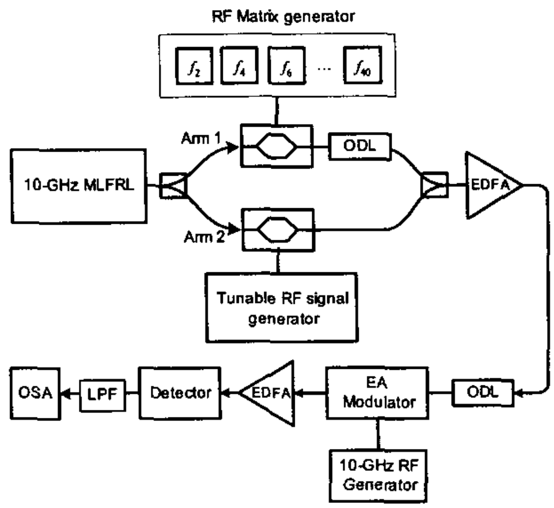

Fig. 6 Experimental Setup: (a) (b) OTDM-based nonlinear distortion reduction scheme using OS-SCM.

Fig. 6 shows the experimental setup used to investigate the performance of the distortion reduction scheme. The optical pulse train generated by MLFRL was split into two arms, each passed through an optical modulator. The one passing through arm 1 was modulated by a matrix generator while the other passing through arm 2 was optionally modulated by a tunable RF generator. The two pulse trains were then time-multiplexed using optical delay line (ODL) and coupler to form a 20Gb/s OTDM signal. At the receiving end, a 10-GHz electro-absorption (EA) modulator was used to demultiplex one of the time channels for RF spectrum measurement. EA modulator was chosen for OTDM demultiplexing due to its high extinction ratio (~22dB). Since the switching window of the EA modulator was 50 ps, much longer than the mode-locked pulse width, we could safely ignore the distortion induced by non-uniform switching window of the EA modulator.

To determine the linearity of mux-demux process, we first used two subcarrier tones (295.25 MHz and 301.25 MHz) to modulate the two arms separately. One of the arms (the one modulated with 301.25 MHz carrier) was demultiplexed by the EA modulator. The RF spectrum of the demultiplexed waveform (Fig. 7) showed no two-tone-third-order distortions. This indicated that the mux-demux process introduced no nonlinear distortions. In addition, the demultiplexing process showed efficient isolation, i.e., only a very small amount of RF signal carried by the adjacent time slot leaked out to the demultiplexed output. As shown in Fig. 7, the 295.25 MHz RF tone was suppressed substantially by 58.9dB.

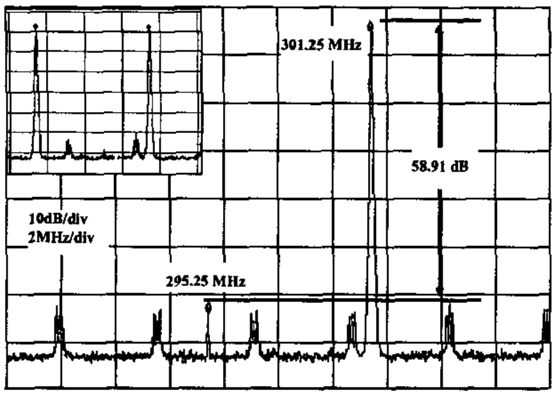

Fig. 7 Two-tone linearity test for mux-demux process. Inset: shows the spectrum of the two RF components before demultiplexing. Central frequency = 297.87 MHz.

To measure the extent of distortion reduction, 20 subcarrier channels were used to modulate arm 1. Arm 2 was left unmodulated as from the previous measurement that optical isolation between the two time-division groups was adequate to suppress additional distortion generated from carriers beating between two TDM channels. Modulated pulse train from arm 1 was then demultiplexed at the receiving end and the CTB value was measured. Trace (c) in Fig. 7 shows the measured CTB value. It is shown that in most of the channels, CTB was reduced by 10 dB when compared with the CW modulation case. These confirmed the effectiveness of our nonlinear distortion reduction scheme.

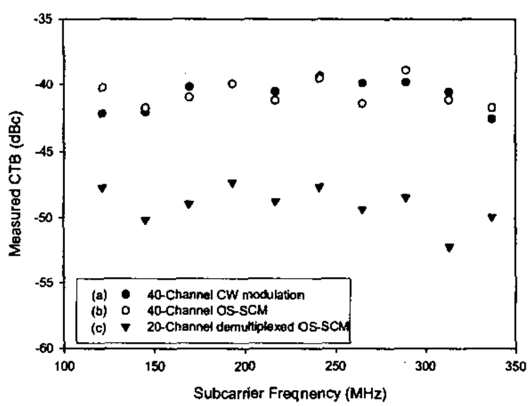

Fig. 8 CTB measurement for (a) 40-channel CW modulation (b) 40-channel OS-SCM (c) 20-channel demultiplexed OS-CM

V. CONCLUSINS

In conclusion, we have proposed and successfully demonstrated a new nonlinear distortion reduction scheme for subcarrier multiplexing system with the use of optical sampling and OTDM mux-demux. Subcarrier frequencies originally intended to be transmitted on a single wavelength channel are separately modulated onto different time channels. The time domain isolation has reduced the number of RF frequencies contributing to IMD. Experimental results showed that the use of OS-SCM induced negligible nonlinear distortion and the OTDM mux-demux process was able to provide sufficient isolation while introduced no additional nonlinear distortions. A CTB reduction of 10 dB is observed for a 40-channel SCM system.

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