Raman Crosstalk Suppression in CATV Overlay Passive Optical Network

Hoon Kim, Sang Bae Jun, and Yun C. Chung

***Abstract*—In cable television (CATV) overlay passive optical networks (PONs), where a CATV signal copropagates with a downstream baseband signal, the crosstalk components mediated by stimulated Raman scattering (SRS) limit the performance of low-number CATV channels. In this letter, we propose and demonstrate a way of reducing the SRS-induced crosstalk in CATV overlay PONs. The proposed scheme utilizes a high-speed polarization scrambler in the transmitter to make the SRS-induced crosstalk independent of polarization evolution along the fiber and a subtractor module to compensate for the crosstalk. Our demonstration shows that crosstalk can be reduced by 9 dB.**

***Index Terms*—Cable television (CATV), crosstalk, fiber nonlinearity, passive optical network (PON), stimulated Raman scattering, wavelength-division multiplexer.**

I. INTRODUCTION

STIMULATED Raman scattering (SRS) is one of the biggest obstacles in cable television (CATV) overlay passive optical networks (PONs), where a 1550-nm subcarrier-multiplexed CATV signal copropagates with a downstream baseband signal carried at $1480 \sim 1500$ nm [1]–[4], [6]–[9]. The power fluctuations of the intensity-modulated baseband signal are transferred onto the CATV signal by the SRS process and degrade the video quality of CATV channels. When the baseband signal is a continuous random bit stream, the crosstalk can be seen as noise on CATV channels, and thus affects the carrier-to-noise ratio (CNR) of CATV channels [1]. On the other hand, when the baseband transmitter generates a periodic idle code word, as can be seen in Ethernet-PONs (E-PONs) of IEEE 802.3ah standard, to facilitate clock synchronization and provide a continuous fill pattern, the crosstalk can be seen as spurious tones, and consequently affects the composite second-order (CSO) or composite triple-beat (CTB) performance of CATV channels [2]. Since the CSO/CTB requirements are generally more stringent than the CNR requirement in CATV systems, the CSO/CTB degradation by SRS can limit the performance of CATV overlay PONs.

There have been some efforts to mitigate SRS-induced crosstalk [3], [4], [6], [7]. One way of reducing the crosstalk is to decrease the wavelength spacing between the baseband and CATV signals [3]. In many PONs, however, the minimum wavelength spacing is specified by the standards and recommendations (e.g., baseband channel wavelength 1480–1500 nm, CATV channel wavelength 1550–1560 nm, in broadband-PON of ITU-T G983.3), and thus there is not much room for a system designer to change the wavelength spacing. Another way to cope with the crosstalk is to decrease the optical power of the baseband signal [4]. Since SRS crosstalk depends on the square of the average optical power of interference signal (i.e., the baseband signal in our case), a 1-dB reduction in baseband optical power can lead to a 2-dB improvement in the CSO/CTB performance of CATV channels [5]. The biggest concern of this approach, however, is that it sacrifices the power budget of baseband signals, possibly resulting in the reduction of the transmission distance or splitting ratio. A pre-emphasis technique, in which a modest increase in the optical modulation index (OMI) is applied to low-number CATV channels, can also remedy to some extent the CSO/CTB degradation for those channels at the slight expense of a CSO/CTB increase in other CATV channels [6].

In this letter, we propose and demonstrate an SRS crosstalk reduction technique that does not induce the performance degradation of baseband and CATV signals. Our scheme employs a high-speed polarization scrambler at the CATV transmitter and an electrical subtractor module at the receiver. Since the SRS process is highly polarization-dependent, we first depolarize the CATV signal using the polarization scrambler and then compensate for the crosstalk with the subtractor module. Our experimental demonstration shows that the proposed scheme can reduce SRS crosstalk by 9 dB.

II. CHOICE OF POLARIZATION SCRAMBLING FREQUENCY

In this section, we determine the modulation frequency of the polarization scrambler since the improper choice of frequency would make crosstalk components added by polarization scrambling fall into the CATV channel band and thus degrade the CSO/CTB performance. In CATV overlay PONs, a CATV signal carrying N video channels suffers from SRS crosstalk. Assuming no depletion of the baseband signal, we can express the normalized optical power of the CATV signal as [5]

$$P_{\mathrm{CATV}} = [1+2\mathrm{SRS}_{\mathrm{DC}}+2\mathrm{SRS}_{\mathrm{AC}}] \cdot \left[1+\sum_{i=1}^{N} m_i \cos(\Omega_i t+\theta_i)\right] \tag{1}$$

where $\mathrm{SRS}_{\mathrm{DC}}$ is the DC Raman crosstalk, $\mathrm{SRS}_{\mathrm{AC}}$ is the AC Raman crosstalk, m_i is the OMI for CATV channel i, Ω_i is the angular frequency of CATV channel i, and θ_i is the initial phase of channel i. The detailed expressions for $\mathrm{SRS}_{\mathrm{DC}}$ and $\mathrm{SRS}_{\mathrm{AC}}$ can be found in [5]. When high-speed polarization scrambling

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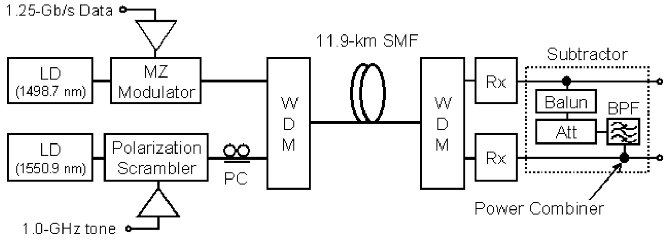

Fig. 1. Experimental setup. Rx: receiver. Att: attenuator. PC: polarization controller.

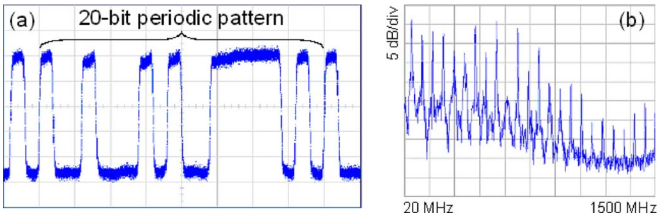

Fig. 2. A 20-bit periodic idle code word measured with (a) an oscilloscope and (b) an RF spectrum analyzer.

with an angular frequency of $\Omega_{\rm ps}$ is applied to the CATV signal, (1) can be modified in the first-order approximation as

$$P_{\rm CATV} = [1 + \{1+\cos(\Omega_{\rm ps}t)\}\,{\rm SRS_{DC}} + \{1+\cos(\Omega_{\rm ps}t)\}\,{\rm SRS_{AC}}] \cdot \left[1+\sum_{i=1}^{N} m_i\cos(\Omega_i t+\theta_i)\right]. \quad (2)$$

In this equation, the polarization overlap factor is now explicitly expressed, and thus should be omitted in $\rm SRS_{DC}$ and $\rm SRS_{AC}$. Then, (2) can be rewritten as

$$\begin{aligned} P_{\rm CATV} \cong & \left[1+\sum_{i=1}^{N} m_i\cos(\Omega_i t+\theta_i)\right](1+{\rm SRS_{DC}}) \\ & + {\rm SRS_{AC}} + {\rm SRS_{DC}}\cos(\Omega_{\rm ps}t) \\ & + {\rm SRS_{DC}}\sum_{i=1}^{N} m_i\cos(\Omega_i t+\theta_i)\cos(\Omega_{\rm ps}t) \\ & + {\rm SRS_{AC}}\cos(\Omega_{\rm ps}t). \end{aligned} \quad (3)$$

Here, we neglect some terms such as the intermodulation components between the AC SRS crosstalk and CATV channels, because m_i is typically much less than one. The first term is the CATV channels boosted with DC SRS gain and the other terms are the AC crosstalk components. The second term is the AC SRS crosstalk, the third term is the crosstalk component coming from the Raman gain modulated by polarization scrambling, the fourth term is the intermodulation components between polarization scrambling and CATV channels, and the last term is the intermodulation components between polarization scrambling and AC SRS crosstalk. Note that due to the polarization scrambling we have additional crosstalk components [i.e., the third, fourth, and fifth terms in (3)]. To prevent these crosstalk components from falling into the CATV channel band, $\Omega_{\rm ps} - \Omega_N$ should be larger than Ω_N, implying that the polarization-scrambling frequency should be higher than twice the highest CATV channel frequency. Here we assume that the highest CATV channel frequency is larger than the AC SRS crosstalk frequency of our interest. This is an appropriate assumption in typical CATV overlay PONs since SRS crosstalk *at low frequency* has the most impact on CATV performance [3], [7].

III. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental setup. The output of a 1498.7-nm laser diode (LD) was modulated with a Mach–Zehnder modulator driven with a 1.25-Gb/s baseband signal. The extinction ratio of the modulated signal was measured to be 12.4 dB. For a video overlay, an LD operating at 1550.9 nm was used. The LD was not modulated in order to observe SRS-induced crosstalk only. The LD output was depolarized by a polarization scrambler driven with a 1.0-GHz sinusoidal tone. The modulator has a V_π (the voltage for inducing a relative TE-TM phase shift of π) of 6.3 V. The two optical signals were multiplexed by a wavelength-division multiplexer and then transmitted over an 11.9-km conventional single-mode fiber (SMF). The length of the SMF was chosen because at the channel spacing of ~70-nm worst-case crosstalk has been known to happen at fiber lengths of approximately 10 km [8], [9]. Fiber launch powers were -10 and 2.5 dBm for the baseband and CATV signals, respectively. The polarization-mode dispersion (PMD) of the fiber was 0.12 $\rm ps/km^{1/2}$. After transmission, the demultiplexed optical signals were detected with receivers. The electrical subtractor module consisted of a balun transformer, an attenuator, a bandpass filter (BPF), and power combiners. The balun transformer, which inverts the polarity of the input signal, acts as a microwave subtractor together with the power combiners. This device can be replaced with an inverting amplifier for integration. The power combiners can also be replaced with microwave couplers or pick-off tees to reduce the insertion loss of the signal path. In our demonstration, the SRS crosstalk located at 62.5 MHz was studied since it limited the performance of the CATV signal. Thus, a BPF centered at 62.5 MHz was employed to compensate for the crosstalk of a nearby CATV channel, Channel 3 located at 61.25 MHz in a standard CATV video carrier.

With the experimental conditions, we calculated the crosstalk at 62.5 MHz. Assuming the OMI of the CATV channels to be 4%, the crosstalk is calculated to be -54.3 dBc. This is about 10 dB worse than the CSO/CTB criteria of hybrid fiber coax networks and should be reduced by proper system design or crosstalk compensation. On the other hand, the crosstalk at 125 MHz is calculated to be -64.5 dBc and does not exceed the criteria.

Fig. 2 shows the 20-bit periodic pattern and its RF spectrum. We assumed an E-PON system having an idle code word of “10010 00101 00111 11010”. Since the downstream baseband signal is running at 1.25 Gb/s, the pattern generates spikes spaced by 62.5 MHz in the spectrum of Fig. 2(b).

We first measured the degree of polarization (DOP) of the CATV LD output as a function of the driving voltage of the polarization scrambler, as shown in Fig. 3(a). The DOP decreases nearly linearly with increasing driving voltage. It is expected to be decreased until the driving voltage reaches V_π of the scrambler. The DOP is measured to be <10% when the driving voltage is higher than $0.9 \times V_\pi$. We then measured the power fluctuation of the SRS crosstalk component located at 62.5 MHz while changing the polarization controller at the

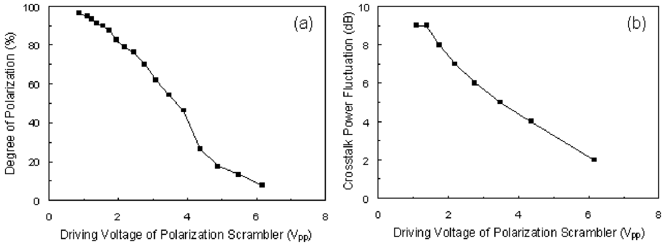

Fig. 3. (a) DOP versus peak-to-peak driving voltage of the polarization controller and (b) power fluctuation of the SRS crosstalk as a function of the peak-to-peak driving voltage of the polarization controller.

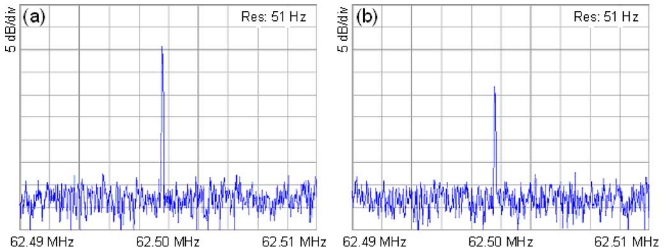

Fig. 4. Measured RF spectra of the SRS crosstalk at 62.5 MHz (a) before compensation and (b) after compensation.

output of the polarization scrambler. Fig. 3(b) depicts the results. In the absence of polarization scrambling, the power fluctuation was measured to be 9 dB due to the polarization dependence of the SRS process. However, as we increase the driving voltage of the scrambler, the power fluctuation is reduced. High-speed polarization scrambling averages out polarization dependence and makes the SRS crosstalk deterministic regardless of polarization rotation along the fiber. Therefore, when the driving voltage is 6.1 V (i.e., DOP $\sim 10\%$), the power fluctuation becomes less than 2 dB.

It should be noted that even in the presence of fiber PMD, the high-speed polarization scrambling is necessary to achieve deterministic SRS crosstalk. Due to fiber PMD and the wide wavelength spacing between baseband and CATV signals, their polarization states may walk off rapidly along the fiber. This acts favorably in randomizing the polarization overlap between the two signals. However, fiber PMD only reduces the occurrence of the worst- and best-case SRS crosstalk, not completely eliminating such cases (see [9] for the detailed analysis on this). On the other hand, high-speed polarization scrambling depolarizes the CATV signal (i.e., makes the DOP of the CATV signal to be 0) and makes the SRS crosstalk insensitive to the polarization evolution *along the fiber*.

Fig. 4 shows the measured RF spectrum of the SRS crosstalk component at 62.5 MHz before and after compensation. In this measurement, the DOP of the CATV LD output was $<10\%$. Without the subtractor module, the crosstalk power is measured to be -99.4 dBm. However, after compensation, the crosstalk power is reduced to -108.2 dBm, about a 9-dB reduction of the crosstalk. In this measurement, we adjusted the polarization controller to maximize the crosstalk. However, it has to be pointed out that the worst-case crosstalk may not be found in our measurements because of the difficulty achieving precise polarization conditions along the fiber [9]. Nevertheless, we believe that our demonstration clearly shows the feasibility of the proposed scheme.

Since the magnitude of SRS crosstalk is dependent upon the fiber length, the attenuation value of the subtractor should be adjusted accordingly. However, this does not necessarily imply that different optical network units (ONUs) in a PON require different attenuation settings. Due to power splitting at the remote node, SRS crosstalk mainly arises in the feeder fiber and the contribution of the crosstalk added at the distribution fiber could be negligible. Therefore, identical subtractor modules could be used for ONUs in a PON where the feeder fiber is shared with the ONUs.

Even though it is not shown in this letter, the proposed scheme can be used to compensate for CNR degradation as well as the CSO/CTB degradation by SRS over a broad range of frequencies. The efficacy of broadband compensation would be dependent upon the bandwidth of the subtractor module. In this case, the BPF in the subtractor module should be replaced with an electrical equalizer the frequency response of which has the inverse of the SRS frequency response.

IV. CONCLUSION

We have proposed and demonstrated an SRS crosstalk suppression technique for CATV overlay PONs. Since the SRS process is highly polarization-dependent, we first depolarize the CATV signal with a high-speed polarization scrambler to achieve deterministic SRS crosstalk and then reduce the crosstalk with an electrical subtractor module. To prevent the intermodulation components between polarization scrambling and CATV channels from falling into the CATV channel band, a polarization-scrambling frequency should be chosen above twice the highest CATV channel frequency. Our demonstration shows that the crosstalk can be reduced by 9 dB when the DOP of the CATV signal is $<10\%$. Further improvement is expected by fully depolarizing the CATV signals.

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