Enhanced Analog Transmission Over Fiber Using Sampled Amplitude Modulation

Jerry C. Chen

***Abstract*—A novel sampled modulation scheme is proposed, allowing the fiber transmission of broad-band analog signals. The deleterious effects of self phase modulation, dispersion and stimulated Brillouin scattering are all mitigated. Comparison with conventional amplitude modulation shows improvement.**

***Index Terms*—Amplitude modulation, harmonic distortion, millimeter-wave radio propagation, optical fiber communication, optical fiber dispersion, optical Kerr effect, optical modulation, optical propagation.**

I. Introduction

FIBER transmission of analog information is important for video and cellular signals. The dominant fiber impairments in a single wavelength system are stimulated Brillouin scattering (SBS) and self-phase modulation (SPM) [1].

For narrow linewidth sources, SBS limits fiber launch powers to a few milliwatts. Larger powers are backscattered and degrade the signal-to-noise ratio (SNR) [2]. Researchers have investigated ways to combat SBS and SPM. For example, phase and frequency modulation [3] can broaden the frequency spectrum of the optical carrier and thereby increase the threshold at which SBS becomes significant to $+16$ dBm. Unfortunately, these additional phase dithers can generate composite second-order (CSO) or second-order intermodulation distortion [4]—a spurious nonlinearity that introduces unwanted RF frequencies.

A specific manifestation of the Kerr effect, SPM creates frequency chirp or phase modulation at the signal's second harmonic. Dispersion then converts the phase modulation to intensity modulation. Called CSO or second-order intermodulation distortion, this intensity modulation has been described by various formalisms [5], [6], and verified by an experiment [7]. The second harmonics generated by CSO limits the transmission of RF signals to an octave. The difference frequencies associated with CSO may complicate the use of erbium-doped fiber amplifiers (EDFAs), because the saturated gain of these optical amplifiers varies with submegahertz optical signals. So, naturally, systems with low CSO are desired. One way to minimize CSO is to reduce SPM or chirp. When given a choice, a system designer would try to use large core fibers and short transmission distances. But chirp will still depend on the optical modulation frequency and optical peak powers. If the chirp is linear, dispersion compensation can cancel the effect of chirp. Although such dispersion management has been demonstrated at one optical wavelength [8], but its extension to multiwavelength, wavelength division multiplexer (WDM) systems is challenging. Furthermore, high-frequency RF signals are particularly susceptible to dispersion [9], which smears out the phase coherence between positive and negative frequency bands. By eliminating one band, single side-band modulation [10] is less sensitive to fiber dispersion. Nevertheless, it is still difficult to design a wide-band transmission link, especially if the link supports a wide range of frequencies and powers.

Here, a novel, sampling scheme, where the analog information is superimposed on a very high repetition rate optical pulse stream is proposed. Because this sampling rate (or pulse reprate) far exceeds the analog modulation frequency, the chirp is affected more by the sampling rate than the data rate, permitting compensation of a wide range of data rates. As a result, the formation of CSO is minimized. In addition, this fast sampling rate broadens the optical spectrum, mitigating the effect of SBS, permitting the transmission of higher optical powers. First, this novel transmitter and receiver will be described in Section II, then how sampling increases the SBS threshold will be discussed in Section III, and how to simulate the fiber transmission of various signals and intermodulations (such as CSO) is described in Section IV. After comparing continuous wave (CW) and sampled techniques for various modulation frequencies, the conclusion is presented with some intuitive remarks.

II. Sampled Transceiver

Normally, high-frequency electrical signals are encoded onto an optical carrier when an external modulator varies the intensity of a CW laser. In high-frequency applications, lithium niobate modulators prevail as they offer low chirp and high-frequency responses. More cost-effective modulators may use electroabsorptive semiconductors. In this paper, we will focus on lithium niobate. Fig. 1 shows the block diagram of an external modulated laser, being modulated by two RF tones—9.5 and 10.5 GHz. Mathematically, the instantaneous optical power can be described by

$$P(t) = \frac{1}{2}P_{\rm avg}\{2 + \sin(2\pi f_1 t) + \sin(2\pi f_2 t)\}$$

where f_1 and f_2 are the signal tones at 9.5 and 10.5 GHz.

In our sampled method, we substitute the CW laser with an optical source that can give short pulses at high repetition rates (Fig. 1). Its repetition rate must be twice the highest RF signal frequency to satisfy the Nyquist criterion. In practice, it is important that this "rep rate" be significantly larger. This prevents

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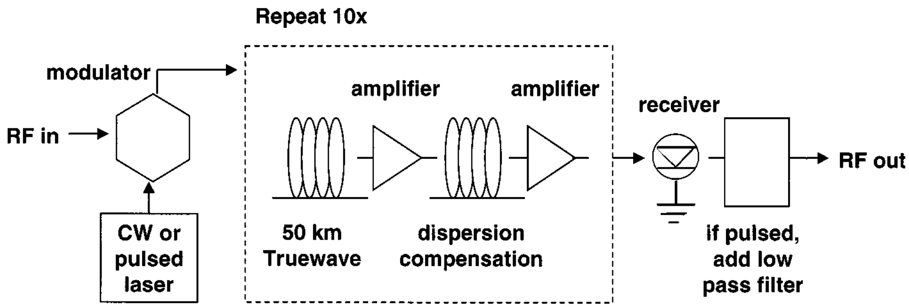

Fig. 1. Block diagram of fiber transmission system using customary transmitter (using CW laser) and our sampled transmitter (using pulse train).

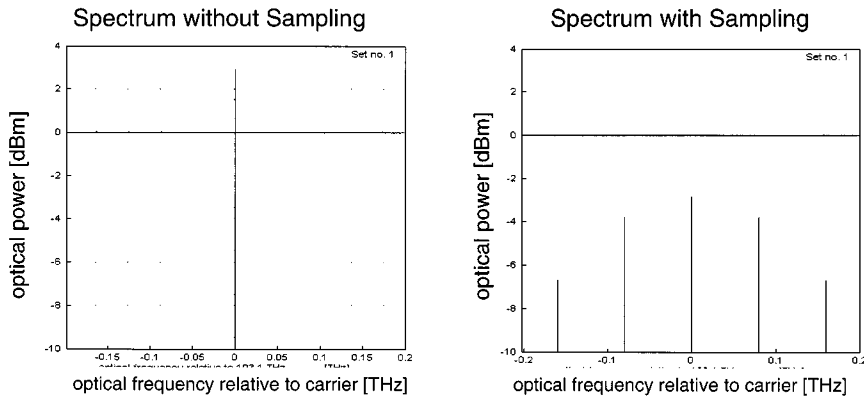

Fig. 2. Optical frequency spectrum of the CW transmitter and the sampled transmitter, before any fiber propagation.

interference and mixing between the signal and the pulses' sidelobes. Here, an 80-GHz "rep rate" to distinguish clearly between the signal harmonics and the pulses' frequencies is chosen. High "rep rate" sources are commercially available from Pritel Inc., Naperville, IL.

The instantaneous optical power of the sampled transmitter as a function of time is

$$\frac{P_{\rm avg}}{2\tau\sqrt{\pi}}\left\{2+\sin(2\pi f_1 t)+\sin(2\pi f_2 t)\right\}\sum_{n=-\infty}^{\infty} e^{-(t-nT)^2/\tau^2}$$

where τ is the pulsewidth and T is the interpulse period (or inverse of repetition rate). The peaks of the pulse intensities form a slowly varying envelope, which is described by the beating of the two sine waves. This envelope resembles the CW case. It is this envelope that carries the information. The pulses are spaced by $T = 12.5$ ps, which is the inverse of the 80-GHz repetition rate. Here, the full-width half-maximum (FWHM) of the pulses is an eighth of the period or $\mathrm{FWHM} = T/8 = 2\tau\sqrt{\ln 2} = 1.56$ ps. To facilitate comparison with the CW laser, the average optical power is kept the same, at 2.0 mW. This translates to a peak power of 30.1 mW. Here, Gaussian pulses are used. Fiber transmission simulations with sechant pulses did not result in a material difference. Changing the pulsewidth affects the chirp, which in turn determines the optimal amount of dispersion compensation.

In the CW case, this modulated light is sent down a fiber. There may be optical amplifiers and dispersion compensating fibers. After some propagation, a diode converts the modulated light back to electricity. Often the optical and electrical signals are amplified. Generally, the receiver consists of diode and amplifier. For high-frequency signals, it is important to add some dispersion compensation before, after or interspersed within the optical medium.

For the sampled case, things are different. Instead of modulating a CW laser (laser with constant intensity), now we modulate a train of pulses. The intensity envelope of the pulse train carries the information. This modulated pulse train is sent over fiber. At the other end, the receiver converts from optical to electrical. Then a filter filters out all the high frequencies content associated with the pulses. What is left is the lower frequencies or the envelope which contains the original signal information.

Instead of a low-pass filter, one could use a bandpass filter (centered around signal frequencies) or an electrical peak and hold circuit (which will filter out high frequencies associated with repetition rate). Alternatively, one can consider the information to be carried by the pulse's energy rather than peak. Then the receiver would use an integrator. This integrator would be optical or electrical, depending on whether it was placed before or after the diode.

III. Mitigation of Stimulated Brillouin Scattering

SBS limits the amount of optical power in a narrow band. In amplitude modulated systems, most of narrow band signals are at the laser's emission frequency. In comparison of sampled and CW transmitters, an average power of 2 mW is used. This is below the SBS threshold of Truewave fiber.

Fig. 2 compares the optical power spectrum of normal CW transmitter and our sampled transmitter. The left plot shows that most of the optical power of the CW transmitter is in the laser emission frequency. Here it is almost 3 dBm. The amplitude modulated sidelobes are very small, having only a few percent of the total power. Putting more optical power in the sidelobes would introduce spurious nonlinearities and intermods, associated with the raised sine transfer function of the $LiNb0_3$ modulator.

For the sampled transmitter, the optical power spectrum is shown in Fig. 2(b). Again, much of the optical power is at the laser emission frequency, although there is significant power at harmonics of 80 GHz away. The pulsed nature of the source tends to smear out the optical spectrum, reducing the power at the laser emission frequency to −2.83 dBm, which is 5.7 dB lower than the modulated CW laser. Shorter pulsewidths will lower the peak power (at the laser emission frequency) even more. This means we can increase the average power further without exceeding the SBS threshold.

Increasing the average power means that the optical signals are larger—further away from the noise floor. This tends to increase the SNR. As the noise is dominated by amplitude spontaneous emission (ASE) noise from the EDFAs, the electrical SNR in a 1-Hz band can be written as

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}^2}{N_{\mathrm{ASE}} P_{\mathrm{avg}}}$$

where P_{avg} is the average optical power, P_{signal} is the optical signal power, and N_{ASE} is the optical ASE noise. Assuming SPM is weak, the signal power is roughly proportional to the average power. Then the SNR improvement can be expressed as

$$\frac{\mathrm{SNR}^{\mathrm{pulse}}}{\mathrm{SNR}^{\mathrm{CW}}} = \frac{P_{\mathrm{avg}}^{\mathrm{pulse}}}{P_{\mathrm{avg}}^{CW}} = \frac{S^{CW}}{S^{\mathrm{pulse}}}$$

where pulse and CW denote the sampled and normal cases. S is the peak power of the optical spectrum divided by the total optical power. In the pulse case, where we have 5.7-dB less power in the spectral peak, we can achieve a 5.7-dB increase in the electrical SNR.

IV. Transmission Simulations

The analog link is simulated with a commercial software package—Virtual Photonic Incorporated's PTDS 1.2. Using the split step Fourier method, this simulator includes self phase modulation, cross phase modulation, Raman, dispersion, and loss. Noise comes from the EDFA and p-i-n. The electrical power spectrum after the modulator before fiber propagation is shown in Fig. 3. This back-to-back propagation involves the transmitter going directly into a p-i-n receiver. The data is represented by tones at 9.5 and 10.5 GHz. Since the modulator is biased at quadrature, there is no second-order intermod at 20 GHz. However, there are signals near 30 GHz and at 8.5 and 11.5 GHz caused by third-order nonlinearities. These third-order terms come from the nonlinear transfer function of the lithium niobate modulator. Marked with a dotted line, the noise floor at −100 dBm comes from the p-i-n receiver. A signal bandwidth of 100 MHz is assumed. The sizable RF power at 80 GHz corresponds to the repetition rate of the pulsed laser. The modulation of the RF signal mixed with this 80-GHz

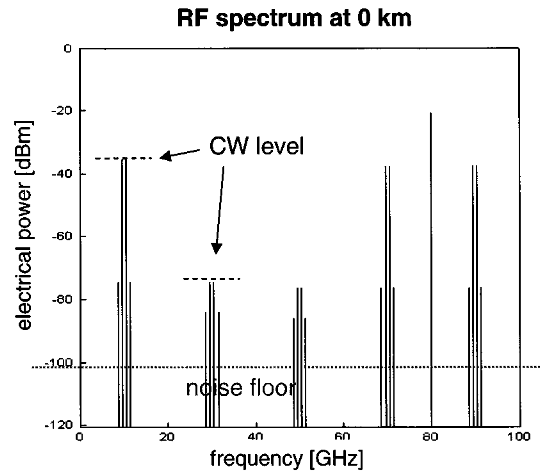

Fig. 3. Electrical or RF spectrum of the sampled transmitter, before any fiber propagation. Dotted lines show CW transmitter's signal and third intermod.

frequency gives the tones around 70 and 90 GHz. There are some RF tones near 50 GHz associated with third-order intermods associated with the 80 GHz repetition rate and fifth-order intermods associated with the signal itself. All these high frequencies can be filtered away without much effect on the signals near 10 GHz. Superimposed on Fig. 3 are dotted lines showing where the CW case's signal and third harmonic lie.

In the first example, the modulated light goes through ten spans, each containing 50 km of Truewave fiber (2.7 ps/nm/km, 0.0667 ps/nm^2/km, $A_{\mathrm{eff}} = 55\ \mu\mathrm{m}^2$, $\alpha = 0.2$ dB/km), 1.69 km of dispersion compensating fiber (−80 ps/nm/km, −0.00186 ps/nm^2/km, $A_{\mathrm{eff}} = 20\ \mu\mathrm{m}^2$, $\alpha = 0.6$ dB/km), and two EDFA. Each EDFA amplifies the signal back to its original 2 mW or 3 dBm, has a noise figure of 4.0, and incorporates a 300-GHz-wide optical filter. The light is then detected by a p-i-n photodiode. The fiber nonlinear index is $n_2 = 2.6 \cdot 10^{-20}$ and the Raman coefficient is 0.3. The net dispersion is zero but residual dispersion slope remains. Neglecting the spans of dispersion compensating fiber, the total propagation distance is 500 km.

The electrical spectrum of the pulsed analog signal after fiber propagation is plotted in Fig. 4. Dotted lines mark the noise floor, CW's signal level, and CW's second harmonic. Note the noise floor is the same for the CW and pulse because they share the same average power. Here the SNR ratio is 117 dB•Hz. Similar to the back-to-back case, the signal terms are at 9.5 and 10.5 GHz, and their third-order intermods appear at 8.5 and 11.5 GHz. Again, their magnitude seems unaffected by fiber propagation. Furthermore, the signal level of −40 dBm is identical to that of the CW case, thus, the SNR is the same. The repetition rate of the Gaussian source gives the RF power at 80 GHz. As before, the signal modulation of the Gaussian pulse train around 10 GHz gives frequency terms near 50, 70, 90, and 110 GHz. What is new is the interplay between SPM and dispersion, creating second-order intermod terms near 0, 20, 60, and 100 GHz. Fourth-order terms also appear at 40 and 120 GHz. The second-order intermod terms, which give rise to CSO, are very small—below the noise floor. Compared to the pulse case, the CSO for the CW case is over 20 dB higher. However, by compensating with a different length of fiber, the CW's CSO

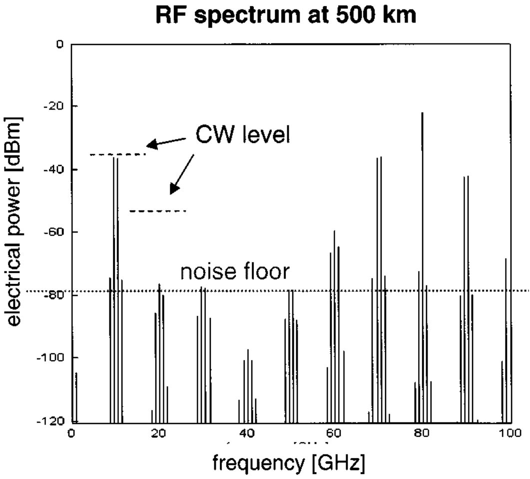

Fig. 4. Detected RF spectrum using the sampled technique, after ten spans, each with 50 km of Truewave, DCF, and two EDFAs. Dotted lines show CW transmitter's signal and second intermod.

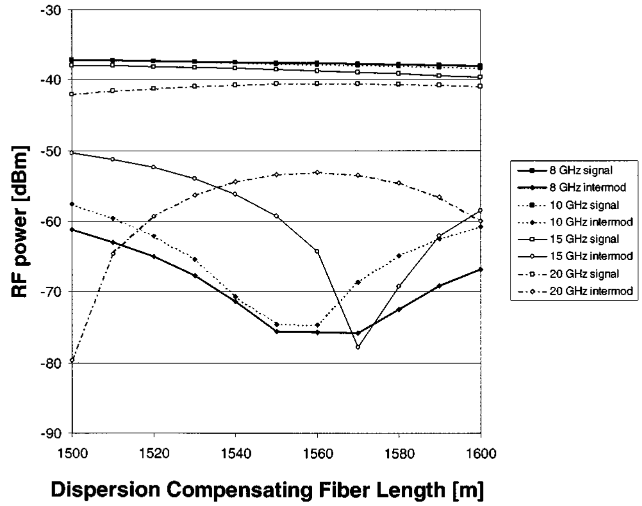

Fig. 5. Using amplitude modulation of the CW source, detected electrical powers of the signal and intermodulations are plotted versus dispersion compensating fiber length, for various modulation frequencies. After ten spans, each with 50 km of Truewave, DCF, and two EDFAs.

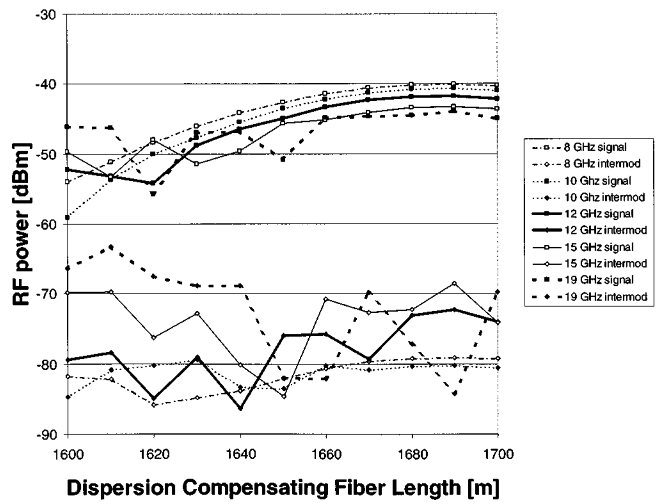

Fig. 6. Using the sampled technique, detected electrical powers of the signal and intermodulations are plotted versus dispersion compensating fiber length, for various modulation frequencies. After ten spans, each with 50 km of Truewave, DCF, and two EDFAs.

can also be suppressed below the noise floor. A major advantage of sampling the optical signal is the relative insensitivity of the second intermod, for varying modulation frequencies. Thus, one can select an appropriate level of dispersion compensation to suppress the CSO for a wide range of modulation frequencies.

To test this, modulated light is sent down ten spans of 50-km Truewave fiber, 1.69-km dispersion compensating fiber (DCF) segments, and in-line EDFAs. As before, the EDFAs boost the optical power back to 2 mW. However, at the last span, the amount of dispersion compensating fiber can be varied, to compensate for any residual chirp. For each amount of dispersion compensating fiber, the electrical signal power and the largest intermodulation product is calculated. Generally, the second-order intermod is larger; it is not fully compensated by the right amount of fiber. However, when the DCF length is optimal for suppressing second-order intermod, the third-order modulation may dominate. Various RF tones spanning over an octave were simulated.

With the CW laser, five different RF signals were simulated. For example, RF tones near 8 GHz (namely, 7.5 and 8.5 GHz) were simulated. Then, tones are stimulated, spaced by 1 GHz, and centered around 10, 15, and 20 GHz. The signals and largest intermods are plotted in Fig. 5 for various lengths of DCF. The amount of DCF for zero net dispersion is 1.687 km. The signal level is around −40 dBm and seems rather insensitive to amount of residual dispersion. In contrast, the point of minimum intermod varies sharply with the amount of DCF. At a fixed modulation frequency the intermod value may vary over 30 dB. Consequently, it would be important to set the DCF length accurately. For 15 GHz, the optimal length of DCF is 1570 m. For tones near 20 GHz, however, this changes to 1500 m. If one were to design a fiber link that can support an octave range of signals, the maximum SNR ratio would be 20.1 dB, which occurs at DCF length of 1600 m.

The sampled transceiver is a bit more immune to variations in modulation frequency. Here, the 1-GHz spaced tones are centered around 8, 10, 12, 15, and 19 GHz. Fig. 6 plots the signal and intermods for various lengths of DCF. Although the average power could be increased by 5.7 dB due to the pulses' mitigation of SBS (Fig. 2), the average optical power is kept at 2 mW to facilitate comparison with the CW case. Compared to the CW case, the signal levels here are more sensitive to dispersion; the 80-GHz repetition rate is taking its toll. The signal level is maximum around 1687 m, where the net dispersion is zero. Having a nonzero net dispersion would broaden or smear out the pulses. Since the receiver has a low-pass filter, detecting peak optical powers, this broadening lowers the signal level. However, the intermod power levels are lower. For nonoptimal values of DCF, they fluctuate by only 20 dB. Furthermore, the intermod levels appear less sensitive to the modulation frequency. As noted before, the pulse repetition rate has a high enough frequency so as to swap out the effect of the slower RF modulation rate. For an octave of signals, the maximum signal to intermod ratio is 27.8 dB occurring at 1680-m DCF. This is over 7 dB higher than the CW case. The amount of DCF could vary by 50 m (or 4 ps/nm) and the signal to intermod ratio would still exceed 24 dB. In conclusion, sampling increases the signal to intermod ratio.

Using pulses to transmit information can be nonobvious since for a given average optical power, their peak power is higher so they should be more sensitive to fiber nonlinearities. Yet, these high repetition rate pulses have a larger frequency content than CW so they are more sensitive to dispersion. Thus, the pulses smear out after a very short distance into the fiber so the pulses resemble CW light; their peak intensity is no longer large, reducing the effect of fiber nonlinearities. One does have to be careful to inject the appropriate amount of DCF to restore the pulses to their original, unsmeared shape. Even then, some residual uncompensated dispersion is acceptable because such dispersion would smear out the pulse slightly. Thus, as long as the pulses do not smear or spread out too much so the pulses overlap significantly, their envelope (and the information) remains intact. In contrast, the CW case does not have a buffer region or temporal dead space between pulses so it is very sensitive to the amount of dispersion compensation. This is evident in how their intermodulation levels vary with dispersion.

V. Summary

Now, intuitively, why does sampling or pulses help out? The interaction of fiber nonlinearities and dispersion makes the optimum design of the fiber transmission system sensitive to the optical power and the signal frequency/bandwidth. Here we introduce pulses with a high repetition rate, so the power and frequencies of these pulses dominate that of the signal. Then an optimal system, with large signal to intermod ratios, is designed around the pulse characteristics. So, a wide range of signal frequencies can now be supported within a single design. In addition, the pulses distribute the power from an otherwise large CW carrier frequency into harmonics of the repetition rate. This mitigates deleterious effects from SBS, which limits the optical power in a given frequency. As a result, now, larger average powers can be transmitted. Larger powers means larger signal to noise ratios.

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