Nonlinear Distortion and Crosstalk in Microwave Fiber-radio Links

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***Abstract* — Dispersion and fiber nonlinearities are potentially significant sources of impairment in fiber-radio links. An experimental study of second harmonic distortion and WDM cross-talk in externally modulated microwave fiber-radio links indicates that these impairments are much more significant than previously observed at CATV frequencies below 1 GHz.**

I. INTRODUCTION

Due to its remarkable success in cable television distribution systems, analog fiber is poised to find widespread application in many other microwave radio systems such as fixed wireless access (FWA) and military communications. In these "fiber-radio" systems, modulated microwave and millimeter-wave radio signals are transported to and from remote antennas or base-stations via optical fiber. This approach allows signal generation and network interfaces to reside in a central station, with a minimum of complexity residing in the remote base-station/antenna.

The design of an operational fiber-radio system requires careful consideration of the optical link performance. The usual considerations include optical loss, laser relative intensity noise (RIN), shot noise at the detector, and nonlinearities in the optical modulator. For fiber-radio systems there are also impairments related to fiber dispersion and fiber non-linearity. These impairments are frequency dependent, and are more significant in the microwave and millimeter-wave bands than previously observed at CATV frequencies (< 1 GHz).

II. SIGNIFICANT NONLINEAR IMPAIRMENTS

A. Second Harmonic Distortion

Consider fiber induced second harmonic distortion (2HD). 2HD impacts performance when a link extends over more than an octave of bandwidth. For instance, 2HD has been investigated for multi-octave CATV systems, but only at frequencies up to 0.8 GHz [1].

In links using external modulation, there are primarily two fiber related sources of 2HD, chromatic dispersion and the fiber's nonlinear refractive index. The contribution from the nonlinear refractive index is expected to be small at the powers used in this study. However, as we shall see, the chromatic dispersion contribution can be quite large. In order to understand how dispersion contributes to 2HD, consider the spectrum of an optical carrier, modulated at a frequency, f_{RF}, by a Mach-Zehnder intensity modulator (MZM) biased at quadrature. As shown in Figure 1, the spectrum consists of optical sidebands at $f_o \pm f_{RF}$, and $f_o \pm 2f_{RF}$. For the purpose of discussion, we neglect the lower-intensity higher-order sidebands. At the photodiode, frequency components at $2f_{RF}$ are generated from the products of f_o and $f_o \pm 2f_{RF}$ as well as the product of $f_o + f_{RF}$ and $f_o - f_{RF}$. Based on the general expressions for propagation in a dispersive fiber [2], it can be shown that with a small modulation index and no dispersion, the second harmonic products cancel by vector addition. However, in the presence of chromatic dispersion, a change in phase relationships between optical carriers generally leads to a nonzero second harmonic component.

Similarly, in the presence of dispersion, the fundamental, f_{RF} will be cancelled at certain frequencies; this is the well-documented dispersion penalty [3]. Although not an explicit contributor to 2HD, a suppressed fundamental enhances the *relative* level of 2HD.

B. Wavelength Division Multiplexing Crosstalk

Many applications, such as FWA can benefit from the use of wavelength division multiplexing (WDM). For example, consider an FWA system where a single fiber feeds an array of cellular base stations. In order to reuse frequencies in neighboring cells, each cell is assigned a dedicated wavelength. Steerable arrays and other "smart" antenna systems can also use WDM to feed each array element with a unique wavelength. In this architecture, all signals pass through a common fiber, and the array is stabilized against relative phase shifts. In these WDM systems, crosstalk between wavelengths must be considered.

Earlier work in WDM CATV systems [4]-[5] points toward two primary fiber-related causes of this type of crosstalk, stimulated raman scattering (SRS) and cross-phase modulation (XPM). In the CATV band, SRS is typically dominant. However, at close wavelengths and/or microwave modulation frequencies, XPM is the larger effect.

XPM follows from the nonlinearity of the refractive index of the fiber. Intensity modulation on a given wavelength channel modulates the fiber's refractive index, leading to phase modulation on channels at other wavelengths. Chromatic dispersion in the fiber then converts the phase modulation into intensity modulation. This manifests itself as crosstalk between WDM channels.

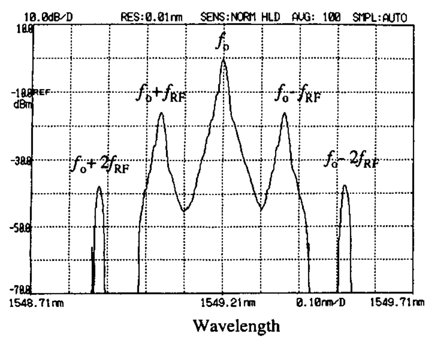

Fig. 1. Optical spectrum of double sideband modulated optical carrier, showing second harmonic components.

III. Measured Performance

A. Second Harmonic Distortion

A simple single-wavelength externally modulated photonic link was set up in order to explore the 2HD performance. The link used a 1.5 μm distributed feedback (DFB) diode laser source, externally modulated by a 20 GHz MZM, biased at quadrature. The MZM was driven to produce a modulation index of 47%, measured at 2 GHz. 10 mW of optical power was launched into 22 km of Corning SMF-28™ fiber, after which a 40 GHz bandwidth photodiode was used to demodulate the RF signal. The modulation frequency was swept in multiple sub-octave bandwidths over a range from 2.5 to 18 GHz. The RF power level at the fundamental frequency, the RF power at the second harmonic frequency, and the DC photocurrent were measured at the photodiode.

Figure 2 shows the 2HD performance of this link. A peak in the second harmonic level occurs near 8 GHz. This represents the point at which the second harmonic beat components add nearly in-phase at the photodiode. As the frequency is further increased, these components become out-of-phase and the 2HD level is reduced. As 13.4 GHz is approached, the carrier frequency becomes suppressed, increasing the *relative* 2HD level.

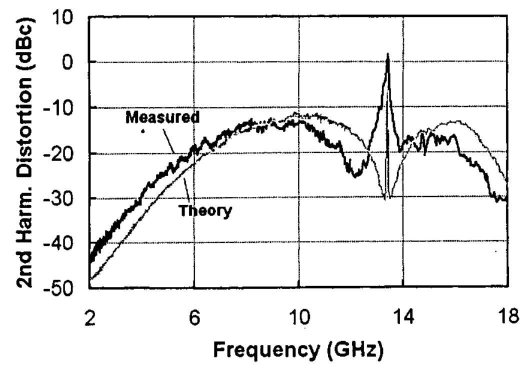

Fig. 2. Second harmonic distortion level vs. fundamental input frequency after 22 km of SMF-28 fiber.

Figure 2 also shows a theoretical prediction for the 2HD level with a dispersion of 16 ps/nm-km. This theoretical prediction follows from the expressions of Corral [2] for a dispersive optical link with double sideband plus carrier. Note that this gives a good fit, even without considering the smaller additional 2HD contribution from the fiber's nonlinear refractive index.

Studies on a typical FWA system [6] indicate that a carrier-to-interference (CIR) ratio of at least –23 dBc is needed for a transparent optical link when QPSK modulated channels are used. Even better CIR performance would be required for QAM modulation. Hence, at frequencies above 5 GHz, this particular link would fail if second harmonic distortion fell in-band. However, the link could be improved by either reducing the optical modulation index, or by employing dispersion management.

B. Wavelength Division Multiplexing (WDM) Crosstalk

Next, a two-wavelength WDM photonic link was set up in order to study crosstalk performance. The link used pair of externally modulated 1.5 μm DFB diode laser sources, spaced 9.5 nm apart. The shorter wavelength, the reference channel, was externally modulated by a quadrature biased, 20 GHz-bandwidth MZM, while the longer wavelength, the crosstalk channel, was unmodulated. The two wavelengths were launched into an SMF-28™ fiber via a WDM multiplexer. Following propagation through 22 km of fiber, the two wavelengths were demultiplexed and detected with 20 GHz bandwidth photodiodes.

As the input was swept from 0 to 18 GHz, the output RF power levels were measured at both wavelengths by a network analyzer. The crosstalk shown in Fig. 3 represents the ratio of RF power received on the initially unmodulated (crosstalk) channel to the RF power received on the modulated (reference) channel.

Also shown is the theoretical prediction for the XPM contribution to crosstalk. The peak near 14 GHz occurs as a result of carrier suppression on the reference channel due to dispersion. Since this carrier suppression effect is typically negligible at CATV frequencies, earlier analyses neglected this factor. However, taking the XPM crosstalk in dB as predicted by Eq. (11) of Phillips [4] and adding to this the dispersion penalty [3] for the reference channel in dB, we arrive at the theoretical result shown in Fig. 3.

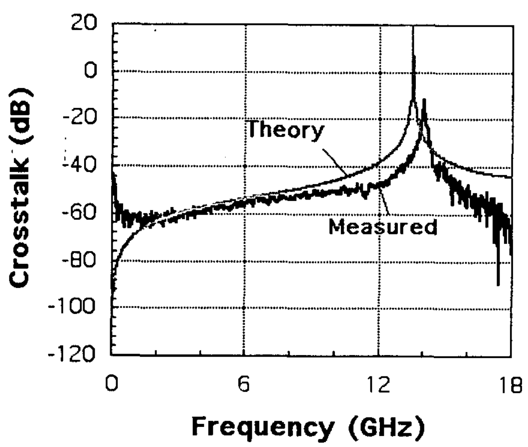

Figure 3. Measured and theoretical crosstalk between WDM channels spaced 9.5 nm apart after 22 km of SMF-28™ fiber.

Our XPM model gives a good fit to the measurement between 2 GHz and 10 GHz. At frequencies below 2 GHz, SRS is expected to be dominant. Since our model does not included SRS, the low frequency fit is not as good. Likewise as we approach 18 GHz, the crosstalk level is somewhat lower than predicted. This is possibly due to carrier suppression on the crosstalk channel, an effect that is not yet included in our XPM model.

IV. Summary

These results underscore the importance of considering fiber induced nonlinear distortion in microwave and millimeter wave analog fiber-radio links. Signal distortion due to WDM crosstalk and 2HD is generally much more significant at microwave frequencies than at the frequencies below 800 MHz used for CATV. 2HD can severely limit the dynamic range of multi-octave links, while crosstalk may significantly impact the design of wavelength multiplexed fiber radio networks.

Since both fiber induced crosstalk between WDM channels and 2HD are enhanced by chromatic dispersion, dispersion management will prove to be paramount to improving performance.

Acknowledgement

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