Adaptive optical post distortion linearization

Jason Chou, Ozdal Boyraz, and Bahram Jalali

Optoelectronic Circuits and Systems Laboratory
University of California, Los Angeles (UCLA)
CA 90095-1594, U.S.A.
Tel: 310-206-4554, Fax: 310-206-2239
jalali@ucla.edu

Abstract: A technique to suppress optical nonlinearities is demonstrated using adaptive optical domain post distortion. The concept, rooted in electrical domain linearization, mitigates optical nonlinearities by generating sidebands that are equal but opposite in phase from the unwanted components. We model and experimentally demonstrate >20 dB extinction in four wave mixing by an adaptive phase controller and computer feedback loop.

OCIS codes: (190.4380) Nonlinear optics, four-wave mixing; (060.4370) Nonlinear optics, fibers.

References and Links

1. M. Nazarathy, J. Berger, J. Ley, M. Levi, and Y. Kagan, "Progress in externally modulated AM CATV transmission systems," J. Lightwave Technol. **11**, 82-105, (1993).
2. R. Sadhwani, B. Jalali, "Adaptive CMOS predistortion linearizer for fiber-optic links," J. Lightwave Technol. **21**, 3180-3193, (2003).
3. J. Basak, R. Sadhwani, B. Jalali, "WDM pilot tone technique for analogue optical links," Electron. Lett. **39**, 1083-1084, (2003).
4. R. H. Stolen and J. E. Bjorkholm, "Parametric amplification and frequency conversion in optical fibers," J. Quantum Electron. **18**, 1062-1072, (1982).
5. H. Taga, "Long distance transmission experiments using WDM technology," J. Lightwave Technol. **14**, 1287-98, (1996).
6. Forghieri, F. Tkach, R.W., Chrapyvy, A.R., "WDM systems with unequally spaced channels," J. Lightwave Technol. **13**, 889-897, (1995).
7. Forghieri, F., Tkach, R.W. Chraplyvy, A.R., Marcuse, D., "Reduction of four-wave mixing crosstalk in WDM systems using unequally spaced channels," Photon. Technol. Lett. **6**, 754-756, (1994).
8. M. W. Maeda, W. B. Sessa, W. I. Way, A. Yi-Yan, L. Curtis, R. Spicer, and R. I. Laming, "The effect of four-wave mixing in fibers on optical frequency-division multiplexed systems," J. Lightwave Technol. **8**, 1402-1408, (1990).
9. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, San Diego, Calif., 1989).
10. H. Takahashi and K. Inoue, "Cancellation of four-wave mixing by use of phase shift in dispersive fiber inserted into a zero-dispersion transmission line," Opt. Lett. **20**, 860-862, (1995).
11. M. E. Mahric, F. S. Yang, M.-C. Ho, and L. G. Kazovsky, "High-nonlinearity fiber optical parametric amplifier with periodic dispersion compensation," J. Lightwave Technol. **17**, 210-215, (1999).
12. J. Kim, O. Boyraz, J. H. Lim, M. N. Islam, "Gain enhancement in cascaded fiber parametric amplifier with quasi-phase matching: theory and experiment," J. Lightwave Technol. **19**, 247-251, (2001).

1. Introduction

Electronic pre- and post- distortion techniques have proven to be a highly versatile technique for suppressing intermodulation distortion in RF and optical communication links [1-3]. These techniques rely on intentional generation of intermodulation tones that are equal in amplitude and opposite in phase to those produced by the nonlinear device or the transmission medium. Both these functions, i.e. generation and shaping of intermodulation tones, are performed in the RF domain. Adaptive digital control of the generated intermodulation tones is highly desired in order to achieve large distortion suppression and stable operation.

Although electronic linearization techniques have been advantageous for narrowband applications, performing linearization in the optical-domain would offer much greater bandwidth. In this paper, we propose and demonstrate an optical-domain adaptive post distortion linearization of an optical link. As a proof of concept, the system is used to adaptively suppress Four Wave Mixing (FWM) components produced by the third order nonlinearity of optical fiber. The adaptive control is the key in producing a robust solution where a high level of FWM suppression is achieved for a wide range of optical powers and fiber lengths.

2. Approach

The concept of an adaptive optical post distortion linearizer is illustrated in Fig. 1(a). Consider an *n*-channel WDM transmission link impaired by FWM. An arbitrary pair of channels located at λ_1 and λ_2 generates nonlinear sidebands at λ_{f1} and λ_{f2}. These unwanted components will cause interference and crosstalk between neighboring WDM channels. FWM in fiber has been studied extensively and its effect on communication systems is well known [4-8]. In order to reduce the impairment, an adaptive optical post distortion linearizer, described here, attenuates the sidebands in a nonlinear medium by creating FWM components that are similar, but opposite in phase, to the original. The technique can be described in two stages. First, a precise and adaptive phase shift is induced onto the FWM sidebands at λ_{f1} and λ_{f2}. Second, a nonlinear fiber generates a new pair of FWM components at λ_{f1} and λ_{f2}, 180 degrees out of phase from the old waves. The sidebands will experience destructive interference at the output. As a result, the FWM components from the link are suppressed, mitigating crosstalk in neighboring WDM channels. By monitoring the residual FWM distortion, an adaptive phase controller (e.g. spatial light modulator) is adjusted to maintain maximum suppression.

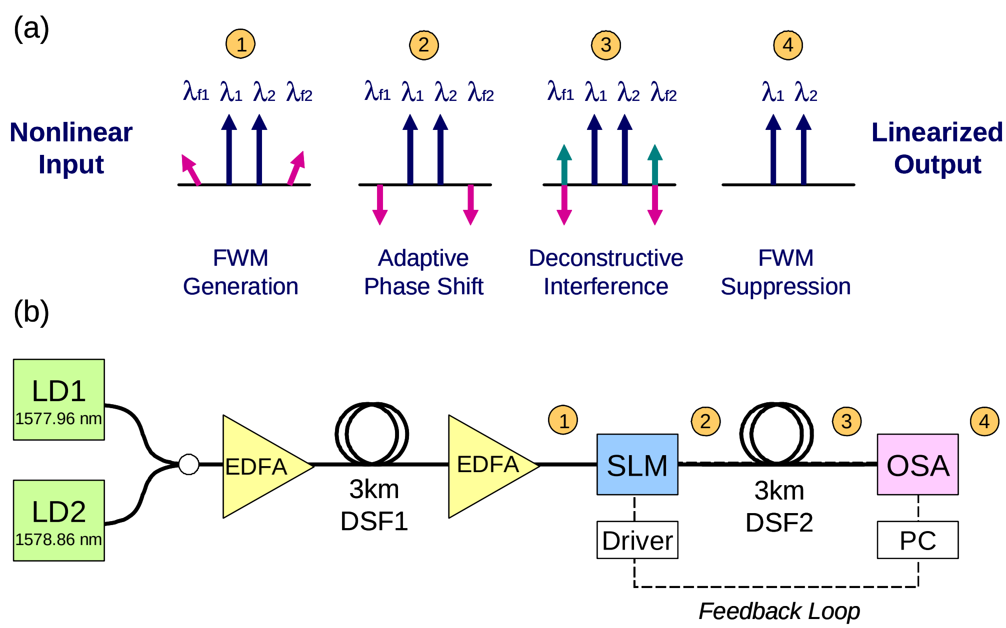


Fig. 1. (a) Basic concept of the Optical-domain Post Distortion Linearizer. (b) Experimental setup. LD: laser diode. SLM: spatial light modulator. DSF: dispersion shifted fiber. EDFA: erbium doped fiber amplifier. PC: personal computer.

#7476 - $15.00 US

Received 16 May 2005; revised 8 July 2005; accepted 12 July 2005

The process of FWM induced crosstalk cancellation and enhancement of parametric gain in a fiber has been previously proposed and demonstrated [4], [9-12]. Here, we present a detailed description and method of an adaptive optical domain post-distortion linearization derived from fundamental equations governing FWM interactions. Our model will provide a physical insight into the key parameters, e.g. channel powers and nonlinear fiber lengths, which will affect the performance of the cancellation. For generality, we will begin with a description of the four coupled wave equations governing the amplitude evolution in a non-degenerate FWM process [9]:

$$\frac{dA_{s,c}}{dz} = i\gamma\left[\left(\left|A_{s,c}\right|^2 + 2\sum_{k\neq s,c}\left|A_k\right|^2\right)A_{s,c} + 2A_1A_2A^*_{c,s}e^{-i\Delta kz}\right] \tag{1a}$$

$$\frac{dA_{1,2}}{dz} = i\gamma\left[\left(\left|A_{1,2}\right|^2 + 2\sum_{k\neq 1,2}\left|A_k\right|^2\right)A_{1,2} + 2A^*_{2,1}A_sA_ce^{i\Delta kz}\right]. \tag{1b}$$

We will assume a degenerate four-wave mixing process in a low-loss medium involving three wavelength components without pump depletion. The amplitude evolution of all three waves reduces to a set of coupled-wave equations [4]:

$$\frac{dA_{s,c}}{dz} = i\cdot\left[\left(k_{s,c} + 2\gamma P_p\right)\cdot A_{s,c} + \gamma P_p e^{i\cdot 2\phi_{po}}\cdot A^*_{c,s}\right] \tag{2a}$$

$$\frac{dA_p}{dz} = i\cdot\gamma P_p\cdot A_p \tag{2b}$$

where, $k_{s,c}$ is the propagation constants of signal and conjugate, γ is the nonlinear factor of the fiber, P_p is the peak pump power, and ϕ_{po} is the initial phase of the pump wave. From hereafter, we will denote the signal wave as the unwanted nonlinear component we aim to suppress. Under a degenerate FWM case, the signal, pump, and conjugate waves are coupled through Eq. (2). Applying this notation to Fig. 1, the signal at λ_{f1} is created by a pump at λ_1 and conjugate at λ_2, and similarly, the signal λ_{f2} is created by a pump at λ_2 and conjugate at λ_1. The exact analytical solution to Eq. (2) can be expressed in matrix form [12]:

$$\begin{bmatrix} A_s(z) \\ A^*_c(z) \end{bmatrix} = \begin{bmatrix} e^{i\cdot\phi_p} & 0 \\ 0 & e^{-i\cdot\phi_p} \end{bmatrix}\cdot\begin{bmatrix} a & b \\ b^* & a^* \end{bmatrix}\cdot\begin{bmatrix} \left|A_{s0}\right|\cdot e^{+i\cdot\varphi_{s0}} \\ \left|A_{c0}\right|\cdot e^{-i\cdot\varphi_{c0}} \end{bmatrix} \tag{3}$$

where

$$a = \cosh(gz) + i\cdot\frac{\kappa}{2g}\sinh(gz) \tag{4a}$$

$$b = i\cdot\frac{\gamma P_p}{g}\cdot e^{i\cdot 2\phi_{p0}}\cdot\sinh(gz) \tag{4b}$$

$$\kappa = \Delta k + 2\gamma P_p \tag{4c}$$

$$g = \sqrt{\left(\gamma P_p\right)^2 - \left(\frac{\kappa}{2}\right)^2}\,. \tag{4d}$$

ϕ_p is the accumulated nonlinear phase of the pump wave and $|A_{p0,s0,c0}|$ and $\varphi_{p0,s0,c0}$ are the initial field amplitudes and phases of a pump, signal, and conjugate, respectively. The matrix elements *a* and *b* are complex numbers that determine the changes in amplitude and phase of signal and conjugate waves. When $\lambda_p < \lambda_0$, Δk is always positive and consequently *g* is always purely imaginary. Therefore, the hyperbolic functions in (3) can be converted to

#7476 - $15.00 US
Received 16 May 2005; revised 8 July 2005; accepted 12 July 2005

corresponding trigonometric functions. On the other hand, if $\lambda_p > \lambda_0$, g will always be purely imaginary for $P_p < |\Delta k|/4\gamma$. In either case, the resulting intensity of the nonlinear signal, as a function the interaction length z and input field parameters, is found to be [11,12]:

$$|A_s(z)|^2 = |a|^2 \cdot |A_{s0}|^2 + |b|^2 \cdot |A_{c0}|^2 + 2 \cdot |a||b||A_{s0}||A_{c0}| \cdot \cos(\varphi_{s0} + \varphi_{c0} + \phi_a - \phi_b) \quad (5a)$$

$$\phi_a = \tan^{-1}\left(\frac{\kappa}{2|g|}\tan(|g|z)\right) \quad (5b)$$

$$\phi_b = 2\varphi_{p0} + \frac{\pi}{2}. \quad (5c)$$

As observed by the interference Eq. (5a), maximum destructive interference of the signal field is achieved when the magnitudes of the first two terms are equal and the argument of the cosine is an odd multiple of π. Written in terms of an optimal interaction length, $z_{\mathrm{opt}} = L$, and the initial phase values, φ_{p0}, φ_{s0}, φ_{c0}, two necessary and sufficient conditions for maximum suppression are:

$$L = \frac{1}{|g|}\arcsin\left[\frac{|A_{c0}|^2}{|A_{s0}|^2}\left(\frac{\gamma|A_{p0}|^2}{|g|}\right)^2 - \left(\frac{\kappa}{2|g|}\right)^2 + 1\right]^{-1/2} \quad (6)$$

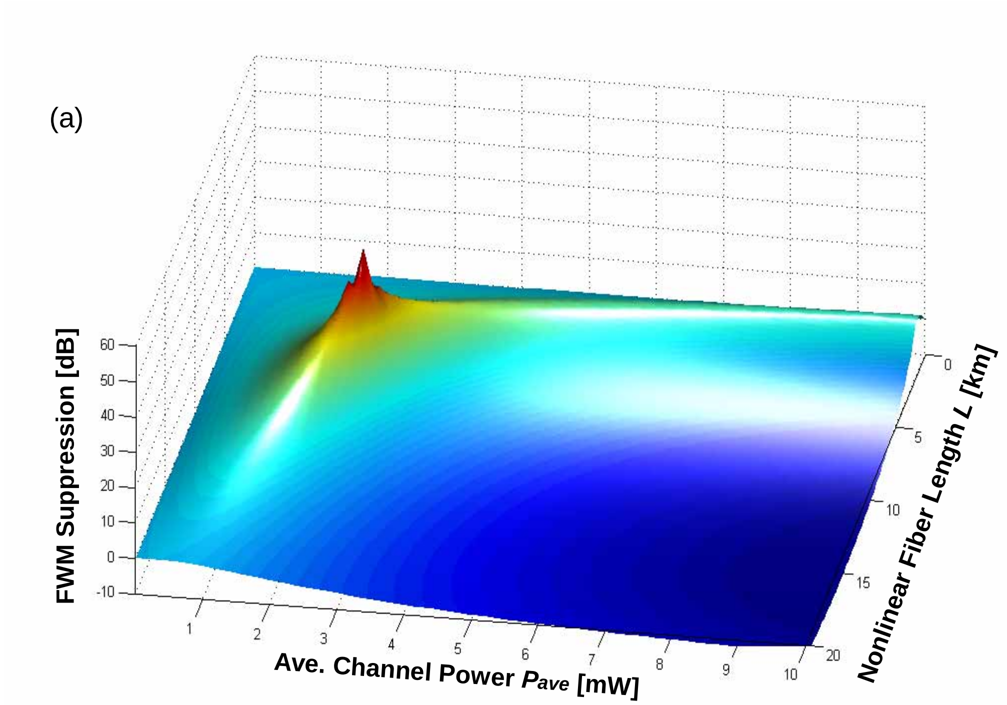
$$\varphi_{s0} + \varphi_{c0} - 2\varphi_{p0} + \xi = (2n+1)\pi \qquad n = 0, 1, 2\ldots \quad (7)$$

where ξ is initial phase mismatch. Eq. (6) determines the optimal nonlinear fiber length from the powers of all three waves. Eq. (7) specifies their required phase relationship at the input of the nonlinear fiber. When these parameters are simultaneously met, the third-order nonlinearity of the optical link will be completely suppressed.

The magnitude of FWM suppression depends on the degree to which the above conditions are satisfied. If the distortion in the link is deterministic, inserting a fixed length of fiber will be adequate to create a fixed phase shift and cancel the FWM components. Unfortunately, due to nondeterministic nature of the input phase, the approach suffers from the inability to maintain a high degree of linearization. A previous experiment using a fixed delay line achieved only 6 dB of suppression [10]. In the presence of random phase variations of WDM channels, from add/drop modules or environmental factors, Eq. (5) and (6) cannot be simultaneously satisfied using a static scheme. As a result, an adaptive approach is highly desired for achieving an accurate and dynamic linearization of FWM.

Our simulations demonstrate the need for an adaptive phase control in a FWM impaired fiber transmission link. Equation (5a) was used to determine the FWM power as a function of average WDM channel power P_{ave} (equal to $|A_{c0}|^2$, $|A_{p0}|^2$) and nonlinear fiber length L. Fig. 2(a) illustrates the conventional approach where a fixed length of fiber with certain dispersion and nonlinearity characteristics is inserted in the link. The observed attenuation peak shows the point of complete destructive interference, i.e. when Eq. (5) and (6) are satisfied. Since the constant phase shift is unable to adapt to variations of the input phase values, large suppression is only achieved for a specific input phase, P_{ave}, and L. A far more effective approach is the adaptive case, shown in Fig. 2(b). Due to a feedback loop, the FWM attenuation is insensitive to input phase fluctuations. Maximum linearization is possible for arbitrary power levels or fiber lengths. A dynamic phase controller and proper choice of nonlinear fiber length ensure Eq. (5) and (6) will be simultaneously satisfied. Our simulation demonstrates FWM suppression >20 dB which agrees with the experimental results (as shown in Fig. 3(c)).

#7476 - $15.00 US
Received 16 May 2005; revised 8 July 2005; accepted 12 July 2005



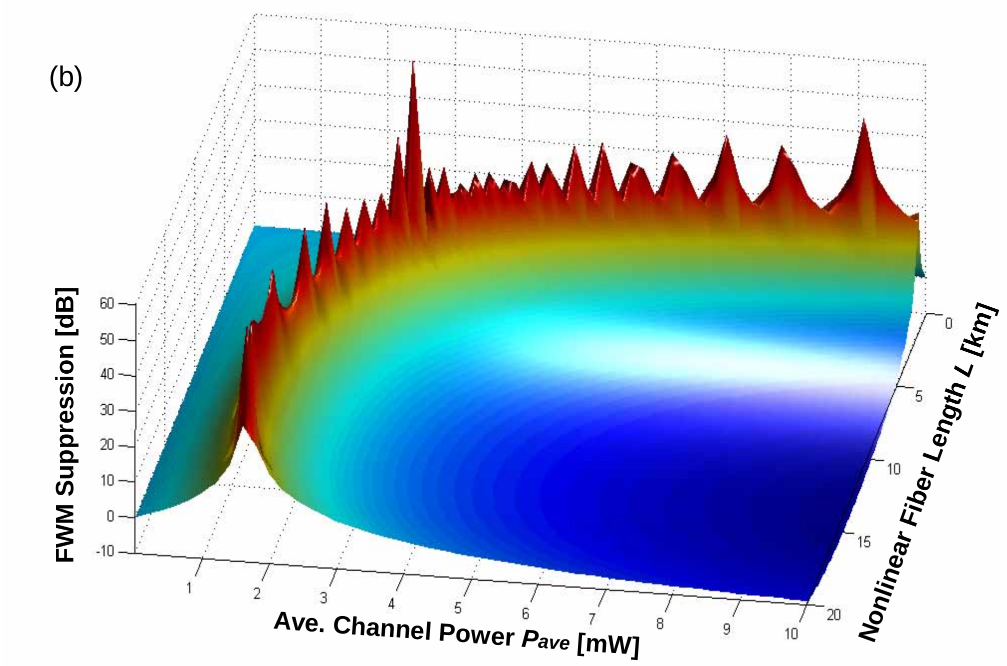


Fig. 2. Simulation of FWM suppression for (a) static and (b) adaptive phase control techniques. Red coloring indicates suppression > 20 dB. An adaptive phase adjustment can provide precision and agility to phase variations at many wavelengths.

#7476 - $15.00 US
Received 16 May 2005; revised 8 July 2005; accepted 12 July 2005

3. Experiment

We experimentally quantify the suppression of FWM components through optical post-distortion linearization by using a spatial light modulator (SLM). Figure 1 shows the experimental setup. Two laser diodes at 1577.96 nm and 1578.86 nm, corresponding to λ_1 and λ_2 respectively, are amplified by an L-Band EDFA. We emulate a FWM impaired transmission link by using a 3.06 km dispersion shifted fiber (DSF1) with λ_0 = 1584.7 nm, GVD slope 0.05 ps/km/nm^2, and nonlinear parameter γ = 2.1 W^{-1}/km. The length of this fiber is chosen without loss of generality. The induced nonlinear crosstalk components are located at λ_{f1} (1576.99 nm) and λ_{f2} (1579.73 nm).

These nonlinearities will be suppressed by the following optical post-distortion section which consists of an SLM followed by a fixed length of DSF. In order to demultiplex the wavelengths, we incorporate a 4-f grating (1000 lines/mm) and lens (20 cm focal length) configuration. The spectral resolution is 0.625 nm. A liquid crystal amplitude/phase spatial light modulator is placed at the focal plane. The SLM consists of 128 pixels which are independently controlled by a computer operated electronic driver, to gray scale accuracy. The finite spectral resolution used with our SLM resulted in residual attenuation dips between each channel. An L-band EDFA is placed before the 4-f configuration to compensate for the system insertion loss of 6.2 dB. Next, a second DSF fiber (DSF2) is used to perform the interference between the new and old FWM waves, made out-of-phase by the SLM. Without loss of generality, DSF2 is identical to DSF1. The average input power of λ1 and λ2 prior to the post distortion linearizer is 3.2 mW. Finally, an optical spectrum analyzer (OSA) measures FWM suppression. This data is feedback to a PC and used to perform a least squares routine that will determine the proper phase shifts used by the SLM to maximize suppression.

Figure 3(a) illustrates the input spectrum before the optical post distortion linearizer. An initial 31 dB power difference between the channels (λ_1, λ_2) and the nonlinearities (λ_{f1}, λ_{f2}) is measured. Assuming degenerate FWM, we define λ_{f1} to be the signal component, while λ_1 and λ_2 to be the pump and conjugate waves, respectively. Likewise, λ_2 and λ_1 are the pump and conjugate, respectively, for λ_{f2}. Figure 3(b) demonstrates the experimental result after FWM is linearized. The maximum attenuation for λ_{f1} and λ_{f2} is 20.74 dB and 15.85 dB, respectively. In this figure, the phase values were chosen such that optimal suppression was selected for λ_{f1}. Figure 3(c) demonstrates a close agreement between our calculations and experimental data. The predicted and measured FWM power is plotted as a function of relative phase between the three waves (as defined by Eq. 5). The advantage of our adaptive scheme is clearly observed near the extreme suppression phase where the sensitivity is measured to be 10 dB per 0.25 radians.

4. Discussion

By monitoring the FWM degradation and controlling the phase for individual channels, FWM suppression can occur over many wavelengths. Such a scheme represents a significant improvement over a fixed delay line that provides suppression at a single channel [10]. In the adaptive scheme, a computer feedback can monitor and control the phase of individual channels to create a phase map that will globally minimize crosstalk. Since a phase solution for a single channel involves a total of three channels, as described by Eq. 7, a global suppression can be reached by fixing two channels and varying the phase of the third. One possible algorithm which could be implemented suppresses the FWM at channel *i* by adjusting the phase at channel *i*+2. When performed sequentially over n channels, the phase map for each channel is individually optimized until all channels achieve FWM suppression.

An important consideration in WDM links is how to measure the FWM amplitude used by the feedback algorithm. In a standard WDM system, FWM components fall at the location of channels, and thus cannot be measured directly. However, since nonlinear components and channels share the same wavelength, inline performance measures (e.g. BER or optical Q

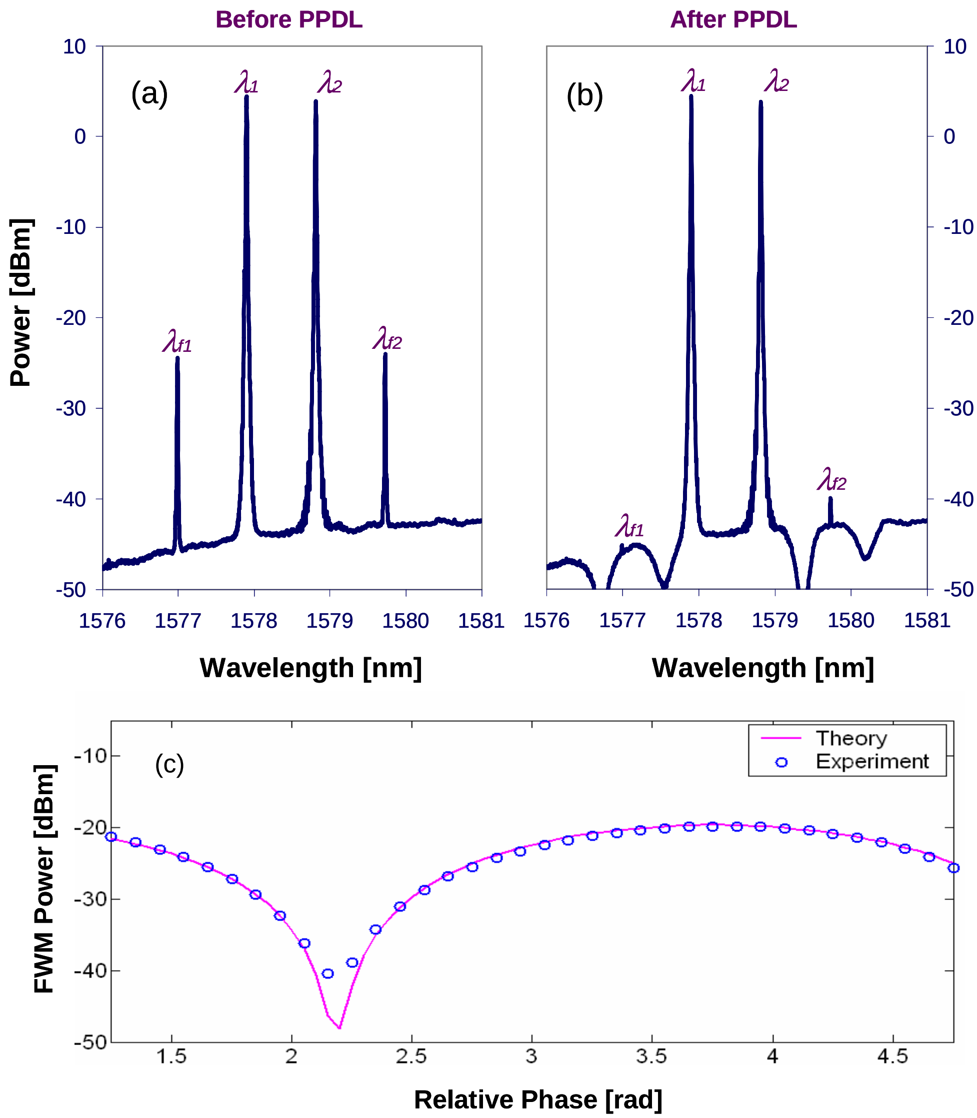


Fig. 3. Optical spectrum measured (a) before and (b) after the Optical-domain Post Distortion Linearizer shows >20 dB suppression. (c) FWM power vs. relative input phase illustrates the sensitivity of the nonlinear attenuation to variations in phase.

value) may be used to reflect the magnitude of FWM components. This information can dynamically feed back into a global linearization algorithm. When data is impressed onto the optical waves the effectiveness of this technique will depend on the modulation format. In pure on-off keying, the FWM impairment will be constant over many bit periods and may be mitigated by a feedback loop. However, in communication systems using random phase modulation, such as DPSK, a fast feedback loop on the order of a bit period would be required for dynamic post compensation. PMD will also affect the phase matching condition, and hence, the efficiency of FWM locally. Since the FWM suppression occurs at the receiver, the feedback algorithm can adapt to these changes, provided that the time period of the fluctuations are relatively slow. By using the feedback algorithm, any environmental variations can be compensated. The amplified spontaneous emission (ASE) introduced by

#7476 - $15.00 US Received 16 May 2005; revised 8 July 2005; accepted 12 July 2005

EDFAs in a transmission system will affect the overall dynamic range of this technique. The final compensation will be limited by an ASE noise floor, below which this technique will not be able to suppress FWM. A more detailed study is necessary to investigate the effectiveness of this approach in a practical transmission system.

One challenge with this technique is to mitigate all FWM products which coexist at a single channel. Since each FWM product has a unique phase map, a global phase solution may not suppress all the FWM products at a single channel. One solution is to mitigate only the most dominant FWM contributions. In a WDM system, this corresponds to FWM components generated by adjacent channels (first-order). The nonlinear efficiencies involving non-adjacent (higher-order) channels reduce as their wavelength separation increases. Depending on the wavelength spacing and channel power, an optimum phase solution will minimize FWM induced cross talk for all WDM wavelengths.

5. Conclusion

In summary, we have introduced an adaptive optical domain post distortion linearization technique. The concept has its root in electrical domain linearization techniques [1-3], but offers much greater performance in terms of bandwidth. As a proof of concept, we demonstrate the suppression of four-wave mixing in the context of a WDM link. The method utilizes an adaptive phase controller and optical post-distortion to destructively interfere FWM components. Compared to previously demonstrated FWM cancellation schemes [10] the new approach works for arbitrary fiber lengths or signal power levels. We have theoretically shown and experimentally verified > 20 dB extinction of FWM using an SLM, 3km of DSF fiber, and adaptive feedback from an OSA.

Acknowledgments

This work is supported by DARPA. The authors are grateful to Dr. Jagdeep Shah for his support of this work.