Reduction of Nonlinear Optical Self Phase Modulation in Optical Fiber at 40 Gb/s

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ABSTRACT

A nonlinear Schrodinger equation has been solved in order to establish the nonlinear optical self phase modulation (SPM) actual magnitude in fiber (within optical domain), the SPM magnitude was simulated at 40 GHz in relation to normalized time and actual distance within the fiber. When the SPM signal comes out of the fiber and enters a pre-designed transimpedance amplifier (TIA) (electronic domain), and according to simulation, the SPM signal corresponds to an input noise spectral density of 320.3 pA^2/Hz (electronic domain) that enters the TIA. A significant reduction in S_{21} scattering parameter, nonlinear optical power and nonlinear noise figure were registered when the 320.3 pA^2/Hz is entered at the TIA input. That effectively means a reduction in SPM value using the TIA at 40 GHz. A Microwave Office software was used for simulation.

Keywords: SPM, Nonlinear Optical, NLO Impairments.

40

(SPM)

.   40

(   )(TIA)

.   (320.3 pA^2/Hz)

S_{21}

(TIA)   (320.3 pA^2/Hz)

.   (Microwave Office)   .SPM

.   :

INTRODUCTION

Experimental performance evaluation of SPM compensation and its application in optical transport network was introduced by (Yamazaki *et al.,* 2010). Experimental results showed transmission distances of 100 Gb/s signal reaches 16.340 and 12.015 km in single channel 10 channel wavelength division multiplexing (WDM) conditions respectively (Yamazaki *et al.,* 2010).

A double cell, self-phase modulation based optical regenerator was designed and optimized to reduce signal noise and distortion. Investigation on multiple passes through the proposed optical

regenerator showed significant amplitude jitter suppression compared single pass alternatives. An improvement in Q-factor became negligible after only five loops for this system and a double Q-factor is achieved demonstrating the efficiency of the proposed scheme (Bolt and Ensser, 2010).

A multilevel coded modulation system in the presence of nonlinear phase noise for fiber optical communication was introduced. The scheme exploited a 16-point ring constellation with nonlinear post compensation of the self-phase modulation via the Kerr effect. A new set partitioning based on the Ungerboeck approach was introduced to maintain unequal error protection in amplitude and phase direction. Simulation results showed that the proposed system provides up to 2 dB gain over a forward error correcting scheme for a block error rates around 10^{-9}, with the same overhead (7%) and complexity (Beygi et al., 2010).

The effect of dispersion slope of highly nonlinear fiber on the performance of self-phase modulation based 2R-optical regenerator was investigated numerically. This study showed that the dispersion slope has a significant impact on the shape of the transfer function of the regenerator. The dispersion slope can therefore be used together with the dispersion value and the filter offset as an additional parameter to control the performance of the regenerator. (Ghafoor and Petropoulos, 2010).

An analytical study of self phase modulation (SPM) and cross-phase modulation (XPM) was performed for coherent Differential Phase Shift Keying DPSK and ON-OFF (OOK) signal in Non-Return to Zero (NRZ) and Return-to Zero (RZ) modulation format for wavelength division multiplexing (WDM) system employing distributed Raman amplifier (DRA). The study showed that 40 Gb/s RZ-DPSK signal with 33.3% duty cycle experiences minimum XPM and SPM induced crosstalk. The results also revealed that minimum crosstalk was induced in backward pumped DRA among the three pumping schemes i.e forward, backward and bi-directional. Results assumed importance for minimizing deleterious XPM and SPM effects in optical communication system (Anamika, 2013).

Self Phase Modulation in Optical Domain

For pulse evolution in an optical fiber, the nonlinear Schrodinger (NLS) equation governs that as follows (Agrawal, 2001):

$$i\frac{\partial U}{\partial z} = \frac{1}{2}\beta_2 \frac{\partial^2 U}{\partial T^2} - e^{-\alpha z}|U|^2 U \tag{1}$$

U is the pulse optical field within the fiber, z is distance that the pulse moves in fiber, T is pulse periodic time, β_2 is the dispersion coefficient and α is the attenuation coefficient. The actual optical field envelope in fiber is given as (Agrawal, 2001):

$$U(z,T) = \frac{T_o}{[T_o^2 - i\beta_2 z(1+ic)]^{1/2}} exp\left[-\frac{(1+ic)T^2}{2(T_o^2 - i\beta_2 z(1+ic))}\right] \tag{2}$$

The chirping frequency c is set at 1. T_o is considered to be the pulse width.

To start deriving the value equivalent to the self phase modulation (SPM) magnitude which is $e^{-\alpha z}|U|^2 U$ (given in equation 1), equation 2 can be used in which the following s_1 and s_2 parameters can be identified:

$$s_1 = \frac{T_o}{[T_o^2 - i\beta_2 z(1+i)]^{1/2}} = \frac{T_o}{(T_o^2 + \beta_2 z(1-i))^{1/2}}$$

$$s_2 = exp\left[-\frac{(1+i)T^2}{2[T_o^2 - i\beta_2 z(1+i)]}\right] = exp\left[-\frac{(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right]$$

$\frac{\partial U}{\partial z}$ equation is derived as:

$$\frac{\partial U}{\partial z} = s_1\frac{\partial s_2}{\partial z} + s_2\frac{\partial s_1}{\partial z} \tag{3}$$

To satisfy equation (3), the values of $\frac{\partial s_1}{\partial z}$ and $\frac{\partial s_2}{\partial z}$ can be obtained:

$$\frac{\partial s_1}{\partial z} = \frac{\frac{1}{2}T_o\beta_2(1-i)}{(T_o^2 + \beta_2 z(1-i))^{3/2}} = \frac{T_o\beta_2(1-i)}{2(T_o^2 + \beta_2 z(1-i))^{3/2}}$$

$$\frac{\partial s_2}{\partial z} = \frac{1}{2}\frac{(1+i)\beta_2 T^2(1-i)}{[T_o^2 + \beta_2 z(1-i)]^2} exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right]$$

$$= \frac{\beta_2 T^2}{[T_o^2 + \beta_2 z(1-i)]^2} exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right]$$

Therefore, from equation (3),

$$\frac{\partial U}{\partial z} = \frac{\beta_2 T_o T^2}{[T_o^2 + \beta_2 z(1-i)]^{3/2}} + \frac{\beta_2 T_o(1-i)}{2[T_o^2 + \beta_2 z(1-i)]^{3/2}} exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right] \tag{4}$$

After defining $\frac{\partial U}{\partial z}$ which is part of the left hand side of equation (1), the right hand side terms of equation (1) can be defined. Beginning with $\frac{\partial^2 U}{\partial T^2}$, the $\frac{\partial U}{\partial T}$ value is derived first as follows:

$$\frac{\partial U}{\partial T} = s_1 \frac{\partial s_2}{\partial T} = \frac{-T_o T(1+i)}{[T_o^2 + \beta_2 z(1-i)]^{3/2}} \, exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right] \tag{5}$$

Hence,

$$\frac{\partial^2 U}{\partial T^2} = \left[\frac{2T_o T^2}{[T_o^2 + \beta_2 z(1-i)]^{5/2}} - \frac{T_o(1+i)}{[T_o^2 + \beta_2 z(1-i)]^{3/2}}\right] exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right] \tag{6}$$

The other term part of equation (1) which is $|U|^2 U$ can be obtained as follows:

$$|U|^2 = U^*.U = \frac{T_o^2}{[T_o^2 + \beta_2 z(1-i)]} \, exp\left[\frac{-T^2 \, T_o^2}{(T_o^2 + \beta_2 z)^2 + \beta_2^2 z^2}\right] \tag{7}$$

$$|U|^2 U = \frac{T_o^3}{[T_o^2 + \beta_2 z(1-i)]^{3/2}} exp\left[\frac{-2T_o^2 T^2}{(T_o^2 + \beta_2 z)^2 + \beta_2^2 z^2}\right] exp\left[\frac{-(1+i)T^2}{2[T_o^2 + \beta_2 z(1-i)]}\right] \tag{8}$$

By multiplying $|U|^2 U$ by $e^{-\alpha z}$, the magnitude of SPM can be obtained. To simulate the magnitude $e^{-\alpha z}|U|^2 U$ against $\frac{T}{T_o}$ and z, the following typical values (at 40 Gb/s) can be set. β_2 is set to 15 ps^2/km, the pulse width T_o is set to 25 ps (@40 GHz), the pulse period T is considered to range from 25 ps to 100 ps, $\alpha = 0.02$ at wavelength of 1.54 µm. The value of z can be up to 0.4 meter. Fig. 1 illustrates the magnitude $e^{-\alpha z}|U|^2 U$ (SPM value) against pulse time ratio $\frac{T}{T_o}$ and distance z.
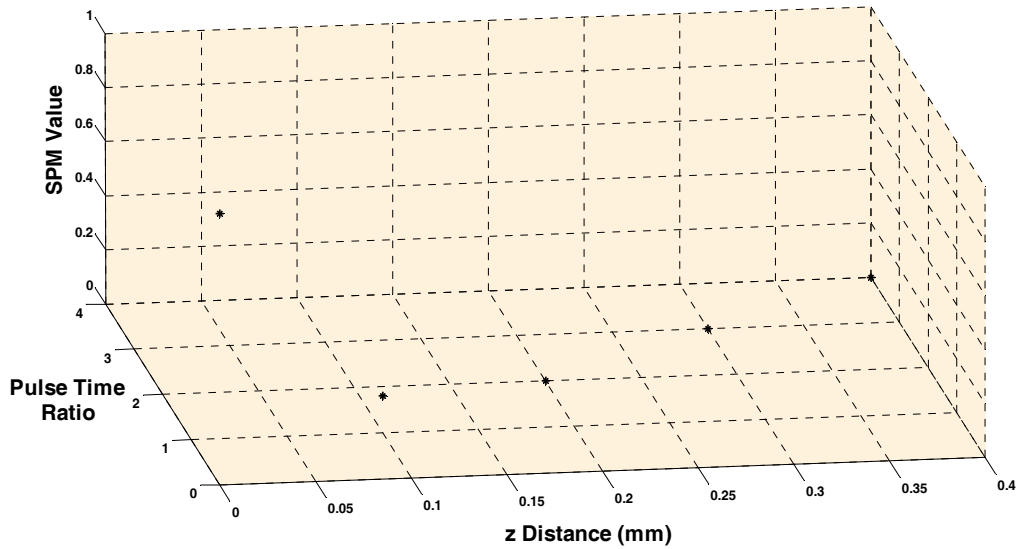

Fig. 1: Self Phase Modulation evolution in terms of pulse time ratio $\frac{T}{T_o}$ and distance z.

SPM Reduction at Electronic Domain

When the signal comes out of the fiber (optical domain carrying SPM noise) and enters a transimpedance (TIA) amplifier (electronic domain), the following work deals with the reduction of that noise. A schematic diagram of a transimpedance (TIA) amplifier electronic circuit is shown in Fig. (2). The RLC FET transistor circuit is commonly used for several purposes, however, it has not been used before as an SPM reducing mechanism. Furthermore, the transistor type used in this work is a high-speed STATZ GaAs FET transistor (Statz *et al.*, 1987) which is used in this work as a new application of TIA amplifier. It is useful to say that $R_F = 148.2$ Ohm (feedback resistor value), $L_F = 0.3$ nH (feedback inductance), $C_F = 91$ pF (feedback capacitance), and $C_i = 1$ pF (input capacitance).

STATZ GaAs FET transistor characteristics can be described in which under normal operating conditions the gate-to-source capacitance is much larger than the gate-to-drain capacitance. At zero drain-to-source voltage, both capacitances are about equal. For negative drain-to-source voltages, the original source acts like a drain and vice versa. Consequently, the normally large gate-to-source capacitance becomes small and acts like a gate-to-drain capacitance. In order to model these effects, it is necessary to realize that there are no separate gate-to-source and gate-to-drain charges, but that there is only one gate charge which is a function of gate-to-source and gate-to-drain voltages (Statz *et al.,* 1987).
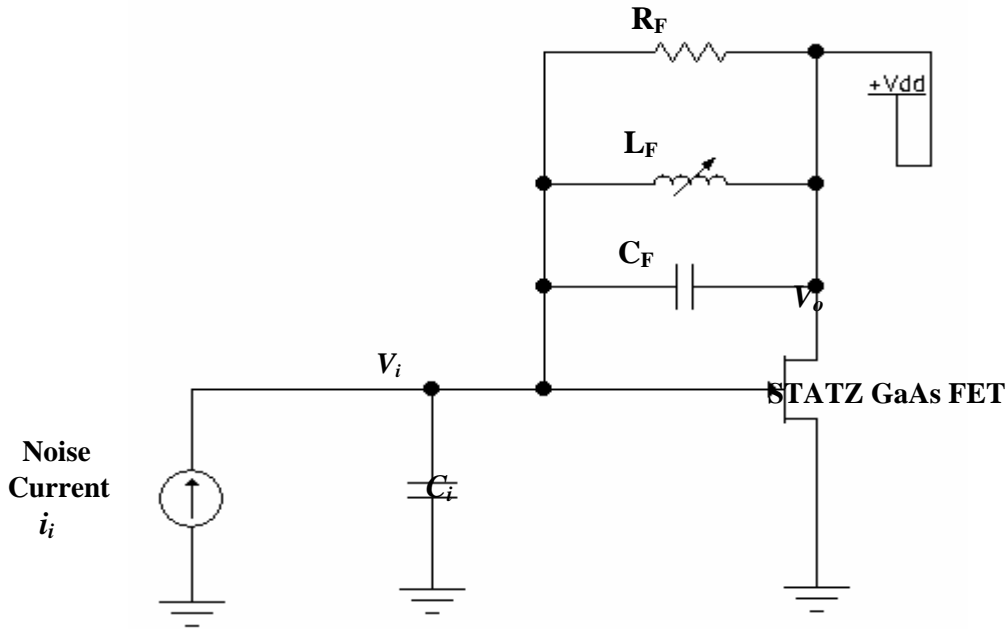

Fig. 2: Transimpedance amplifier schematic design.

In the TIA circuit, the simulated input noise current i_i is entered to correspond to a value of the actual magnitude of SPM which is $e^{-\alpha z}|U|^2 U$ (from optical domain). The best value that worked well (in simulation within electronic domain) for an input noise spectral density was 320.3 pA^2/Hz. We can consider that C_i is the input capacitance, V_i is the input noise voltage (transformed SPM). The output voltage is denoted as V_o.

The transimpedance inverting amplifier voltage gain is given as (Razavi, 2006):

$$\frac{V_o}{V_i} = -A(s) = -A_o \frac{\omega_o}{s + \omega_o} \tag{9}$$

For which $s = j\omega$ is the complex frequency variable, A_o is the amplifier open loop amplifier gain, $A(s)$ is the closed loop frequency dependent amplifier gain, while the value of $\omega_o = 2\pi f_o$ in which f_o is the open loop cut off frequency. The transfer function $\frac{V_o}{i_i}$ of the TIA circuit can be derived in order to show how much of the input noise current is transformed into output voltage (TIA gain $\frac{V_o}{i_i}$).

From electronic circuits principles, the sum of currents at the V_i node is:

$$i_i = \frac{V_i}{\frac{1}{sC_i}} + \frac{V_i - V_o}{\frac{1}{R_F} + \frac{1}{sL_F} + sC_F} \tag{10}$$

From equations (9) and (10), we have:

$$i_i = \frac{V_o}{-A} sC_i + \left(\frac{V_o}{-A} - V_o\right)\left[\frac{s^2 R_F L_F C_F + sL_F + R_F}{sR_F L_F}\right] \tag{11}$$

Multiplying by R_F,

$$i_i R_F = \frac{V_o}{-A} sR_F C_i + \left(\frac{V_o}{-A} - V_o\right)\left[\frac{s^2 R_F L_F C_F + sL_F + R_F}{sL_F}\right] \tag{12}$$

$$i_i R_F = \frac{V_o}{-A} sR_F C_i - \frac{V_o(1+A)}{A}\left[\frac{s^2 R_F L_F C_F + sL_F + R_F}{sL_F}\right]$$

$$i_i R_F = -\frac{V_o}{-A}\left[sR_F C_i + (1+A)\left[\frac{s^2 R_F L_F C_F + sL_F + R_F}{sL_F}\right]\right] \tag{13}$$

Obtaining $\frac{V_o}{i_i R_F}$:

$$\frac{V_o}{i_i R_F} = -A\left[\frac{1}{sR_F C_i + (1+A)\left[\frac{s^2 R_F L_F C_F + sL_F + R_F}{sL_F}\right]}\right]$$

Hence,

$$\frac{V_o}{i_i R_F} = -A\left[\frac{1}{\frac{s^2 R_F L_F C_i + (1+A)(s^2 R_F L_F C_F + sL_F + R_F)}{sL_F}}\right]$$

$$\frac{V_o}{i_i R_F} = -A\left[\frac{sL_F}{s^2 R_F L_F C_i + (1+A)(s^2 R_F L_F C_F + sL_F + R_F)}\right]$$

$$\frac{V_o}{i_i R_F} = -A\left[\frac{sL_F}{s^2 R_F L_F C_i + s^2 R_F L_F C_F + sL_F + R_F + A(s^2 R_F L_F C_F + sL_F + R_F)}\right]$$

We replace A by $A_o \frac{\omega_o}{s + \omega_o}$ as in equation (9):

$$\frac{V_o}{i_iR_F} = -A_o\frac{\omega_o}{s+\omega_o}\left[\frac{sL_F}{s^2R_FL_FC_i + s^2R_FL_FC_F + sL_F + R_F + A_o\frac{\omega_o}{s+\omega_o}(s^2R_FL_FC_F + sL_F + R_F)}\right]$$

$$\frac{V_o}{i_iR_F} = \left[\frac{-sL_FA_o\omega_o}{(s+\omega_o)[s^2R_FL_FC_i + s^2R_FL_FC_F + sL_F + R_F] + A_o\omega_o(s^2R_FL_FC_F + sL_F + R_F)}\right]$$

Multiply by R_F

$$\frac{V_o}{i_i} = \left[\frac{-sR_FL_FA_o\omega_o}{(s+\omega_o)[s^2R_FL_FC_i + s^2R_FL_FC_F + sL_F + R_F] + A_o\omega_o(s^2R_FL_FC_F + sL_F + R_F)}\right]$$

Further simplification indicates that the transfer function of the TIA amplifier is:

$$\frac{V_o}{i_i} = \frac{-sR_FL_FA_o\omega_o}{As^3 + Bs^2 + Cs + D} \tag{14}$$

For which:

$A = (R_FL_FC_i + R_FL_FC_F)$

$B = (L_F + \omega_o R_FL_FC_i + \omega_o R_FL_FC_F + A_o\omega_o R_FL_FC_F)$

$C = (R_F + \omega_o L_F + A_o\omega_o L_F)$

$D = \omega_o R_F(1 + A_o)$

As mentioned earlier, the best value that worked well (in simulation within electronic domain) for an input noise spectral density was 320.3 pA^2/Hz. Therefore, the value of SPM (from optical domain) $e^{-\alpha z}|U|^2U$ should correspond to 320.3 pA^2/Hz of input noise spectral density (electronic domain) in order to have an efficient reduction in SPM. In order to study the reduction in SPM using the TIA configuration, two aspects must be taken into account. The first is how does the S_{21} scattering parameter behave and secondly, what would be the nonlinear noise output power actual magnitude. The S_{21} noise spectrum shows the noise gain reduction for SPM corresponding to 320.3 pA^2/Hz of input current spectral density (electronic domain) at 40 GHz. Figure 3 illustrates the reduction of S_{21} noise spectrum (corresponding to SPM noise at optical domain) at 40 GHz, while at lower frequencies, S_{21} noise spectrum is much higher. At the same time, Fig. (3) includes the TIA gain (transfer function given in equation 14) versus frequency.
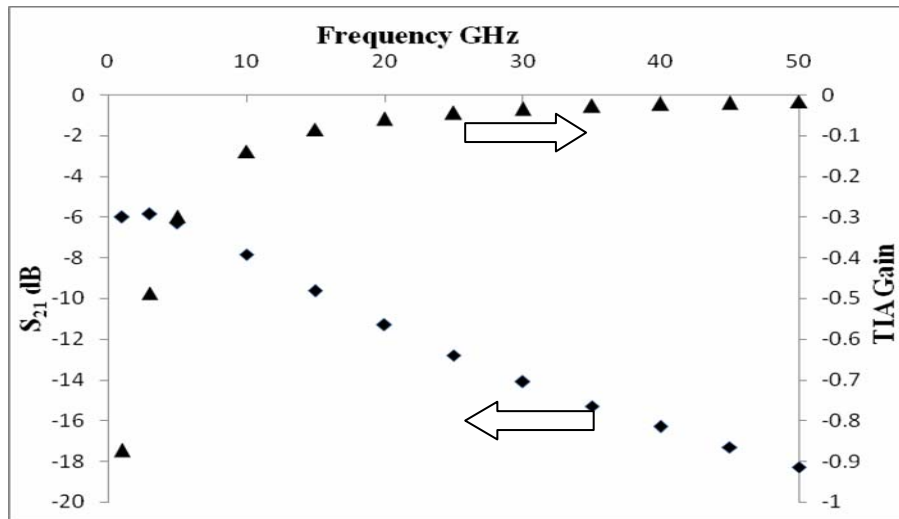

Fig. 3: S_{21} noise spectrum reduction at 40 GHz compared to lower frequencies

From Fig. (3), several comments can be made. To start with, the negative sign of the TIA gain means that the TIA amplifier is an inverting one, and that is clear from the minus sign in equation 14. Furthermore, the TIA gain maintains its strength beyond 40 GHz which is a good efficiency indication. It is important to notice that along side the rise in TIA gain of main signal, there is a downward direction of the noise S_{21} parameter which is highly useful in terms of noise reduction capability. At 40 GHz, both TIA gain and noise S_{21} scattering parameter are the subject of study in this work, although data shown at 50 GHz have shown equally important results. Main fiber optic communication systems focus on 40 Gb/s data bit rate and that explains the reason behind the 40 GHz frequency point. However, the range of up to 50 GHz covers a wide area of fiber optic high data bit rate operating conditions.

The nonlinear noise output power of the transimpedance amplifier when SPM noise is applied that corresponds to 320.3 pA^2/Hz (electronic domain) is shown in Figure 4. A reduction in the nonlinear noise output power is clearly shown at 40 GHz (up to 50 GHz) compared to lower frequencies.
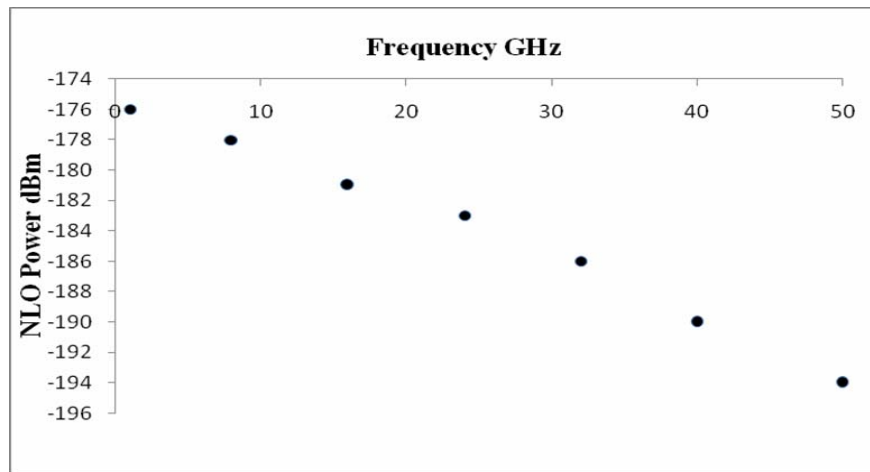

Fig. 4: Nonlinear noise output (NLO) power reduction at 40 GHz compared to lower frequencies.

The nonlinear noise figure (NF) is reduced as in Fig. (5). That implicitly means a real reduction in SPM value, while the transfer function magnitude (equation 14 as TIA gain of main signal) is also embedded in which the TIA gain rise in an opposite direction of the reduced nonlinear noise figure (NF). There is a significant and important gap between the TIA gain and NF at 40 GHz. Further analysis of Fig. (5) indicates that it is possible to make use of data not only at 40 Gb/s but it can also be useful to do that at 10 Gb/s. Although that analysis below 5 GHz may not be that useful due to the fact that the gap between the TIA gain and the nonlinear noise figure (NF) gets narrow. Finally, from Figs. (3 & 5), an inverse relationship between noise (in terms of SM) and TIA gain develops most importantly at 40 GHz and even beyond that. The concept of noise reducing transimpedance amplifier is therefore implemented in this work.
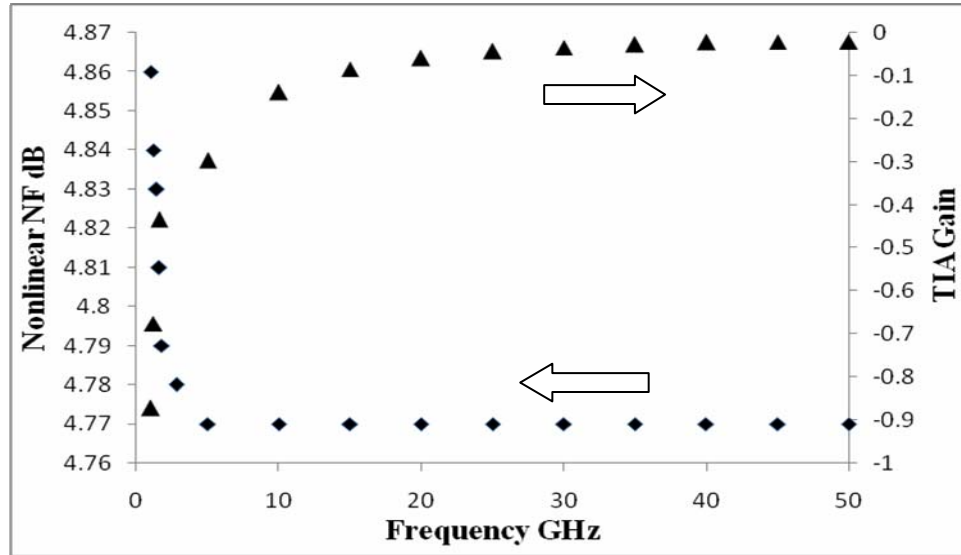
Fig. 5: Nonlinear Noise Figure (NF) reduction range up to 40 GHz.

CONCLUSION

The actual magnitude of self phase modulation (SPM) can be established for 40 GHz signal in an optical fiber. It was confirmed that a significant reduction in SPM can occur when the signal is applied to a STATZ GaAs FET based transistor transimpedance amplifier (TIA). Furthermore, this SPM reduction was demonstrated through the actual reduction in S_{21} scattering parameter, nonlinear optical power and nonlinear noise figure. Another advantage of the TIA system is that alongside the noise reduction, there was a TIA gain (main signal) derived from the TIA transfer function. Although that the input noise spectral density of 320.3 pA^2/Hz is proved to be a good indication of the TIA system capability for noise reduction, however, future research may be possible in improving the system sensitivity in terms of input noise.

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