2017 Twenty-third National Conference on Communications (NCC)

Regeneration of 10 Gbps BPSK Signals Through Phase Sensitive Amplification Coupled with Injection Locking

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***Abstract*—Phase squeezing using phase sensitive amplifier (PSA) typically involves an increase in amplitude noise which when propagated through a multi span link may couple it back into phase through nonlinear processes in the fiber. Through our work we propose and demonstrate a combination of semiconductor optical amplifier based-PSA and injection locking (IL) of semiconductor laser to squeeze both amplitude and phase noise thereby improving the quality of regeneration. We also investigate the effect of the sequence of the two squeezing processes on the quality of regeneration. We conclusively prove that, under optimal operating conditions, appropriate sequencing of amplitude squeezing and phase squeezing is indeed capable of obtaining a better overall noise performance.**

I. INTRODUCTION

Optical amplifiers play a crucial role in fiber optic communication systems. In order to achieve higher data transmission rates over long distances, the amplifiers must not only provide high gain, they must also introduce minimal noise. The noise figure of an *ideal* conventional erbuim doped fiber amplifier (EDFA) is limited by the standard *3 dB quantum limit*. The internal mechanisms of the amplifier that interact with incoming light to generate gain are subject to a certain amount of fluctuations in amplitude and phase due to the quantum nature of light and the amplifier medium. These fluctuations are added to the signal being amplified [1]. This results in the degradation of signal quality. The commercial optical communication systems are adapting advanced modulation formats where the OSNR requirements are becoming stringent. The degradation of OSNR in long-haul links due the EDFAs is the biggest impediment towards extending the reach with advanced modulation formats in such links.

Phase *sensitive* amplifiers on the other hand is not limited by the traditional sources of noise. Specifically, they amplify the in-phase(I) component of the signal and attenuate the quadrature(Q) component[2]. Fig.1 explains the difference between a phase insensitive amplifier(PIA) and a PSA. As shown in part (b) of the figure, the I component experiences a gain while the Q component experiences attenuation. As a result, the output signal is more closely aligned to the I component than to the Q component in phase. This inherent *squeezing* effect due to

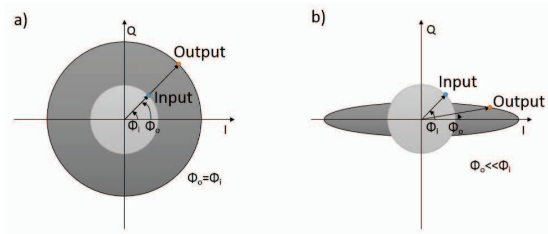

Fig. 1: Representation of the in-phase and quadrature components for (a) phase insensitive amplification (b) phase sensitive amplification.

phase sensitive amplification is useful, for instance, in the regeneration of phase modulated data in BPSK signals. In these modulation formats, information is encoded in the phase of the optical carrier. In presence of laser phase noise, fluctuations in the phase of the carrier causes errors in detecting transmitted symbols. Through the squeezing phenomenon just discussed, it is possible to *route* all the noise to the undetected quadrature, while reducing noise in phase.

The concept of phase squeezing, which is known for more than five decades, was initially proposed and used for making better measurements in interferometry with reduced noise [3]. Caves demonstrated the use of the same concept for noiseless amplification [4]. Over the years, a considerable amount of interest has grown in the practical realization of these devices, which are now referred to as phase sensitive amplifiers. The basic principle of phase squeezing involves the generation of conjugate of the incoming signal and a coherent addition of the signal with the generated conjugate. Amplification is typically associated with the phase-matching conditions being satisfied for the associated parametric process. Nonlinear processes are thus integral to any phase sensitive amplification scheme. Second order nonlinearity in bulk crystals has been used to demonstrate degenerate PSA, both for squeezing [5] as well as low noise amplification [6]. PSAs using third order nonlinearity- such as in highly nonlinear fibers(HNLF)- are more interesting for practical network applications due to ease of availability of such media. In 1991, Marhic et. al [7] demonstrated the first degenerate fiber optic parametric amplifier (FOPA). In 1999, Imajuku et. al. [8], [9] demonstrated PSA with a noise figure of 1.8 dB. Silicon photonic crystal waveguides and semiconductor optical amplifiers have also been used

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978-1-5090-5356-8/17/$31.00 © 2017 IEEE

in the past to demonstrate PSA [10],[11].

Phase sensitive amplification to generate phase-squeezed data might be not be sufficient for commercial communication links that use advanced modulation formats because the ensuing amplitude noise in the process could couple back into phase through nonlinear processes such as cross gain modulation (XPM) and self phase modulation (SPM) while propagating through the fiber. Hence, it becomes important to investigate processes which can be further used to regenerate the signal in amplitude. Another drawback of the fiber based PSA technique is the large footprint of the system, thus with limited possibilities for practical implementation. Therefore, using compact and integrable devices such as semiconductor optical amplifiers(SOAs) would be useful for realizing practical systems. Monolithically integrated PSA devices based on semiconductors have been demonstrated [12], thus corroborating our claim of practically implementable devices with small footprint. Injection locking (IL) of semiconductor lasers has been demonstrated in the past to improve the laser quality [13]. In this paper, we propose a combination of phase squeezer based on four wave mixing (FWM) in SOA for phase regeneration and injection locking of semiconductor laser for amplitude regeneration.

We discuss the numerical study of a PSA device based on the SOA. We demonstrate that the phase matching relation for the four wave mixing (FWM) process in a SOA can be controlled with an appropriate choice of input powers, frequency detuning, input current. We further discuss the impact of the sequence of phase squeezing and amplitude squeezing operations on the overall regeneration performance for a 10 Gbps BPSK signal, using our simulation results. The theory and simulation results to analyze the performance of injection locking and phase sensitive amplification are discussed independently in Section II. The details of the regeneration scheme involving the combination of PSA and IL are discussed in Section III.

II. Theory and Simulations

A. Injection Locking

Injection locking refers to the process of injecting an external optical field from a "master" cavity into a "slave" cavity to control its dynamics. We use the linear gain model as presented in [14] to model the dynamics of the slave cavity.

$$\frac{dE}{dt} = \frac{g}{2}(N - N_{th})(1 + i\alpha)E(t) + \kappa E_{inj}(t) - i(\Delta\omega)E(t), \quad (1)$$

$$\frac{dN}{dt} = J - \gamma_n N(t) - (\gamma_p + g(N(t) - N_{th}))|E(t)|^2, \quad (2)$$

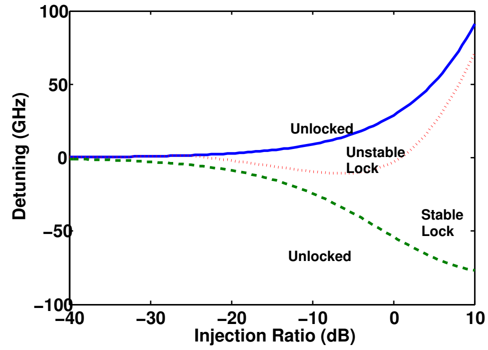

Fig. 2: A typical locking map indicating the phase constraints and its region of stable lock

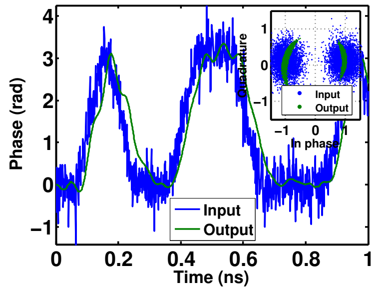

Fig. 3: Time trace and scatter plot of input and output BPSK signals demonstrating regeneration.

where, E, g, N, N_{th}, α, κ, $\Delta\omega$, J, γ_p, γ_n refer to the complex electric field, gain coefficient, carrier density, threshold carrier density, linewidth enhancement factor, coupling coefficient, angular detuning of master from slave, injected carrier density, photon decay rate and carrier decay rate respectively.

The stable locking range for a typical slave-master configuration can be extracted by imposing static phase constraints and small signal stability constraints; for the parameters given in [15], a typical realization of a locking map is shown in Fig. 2. Detuning($\Delta\omega$) is defined as difference between master and slave frequencies ($\omega_m - \omega_s$) and injection ratio (R) is defined as the ratio of injected power to free running slave power and. The figure indicates the range of injection ratios and the allowed detuning to achieve stable locking in this configuration.

The coupled differential equations are solved numerically to obtain electric field and carrier density, for 10 Gbps BPSK data, in the stable locking region. Fig. 3 shows amplitude regeneration using injection locking. The methodology for choosing a specific operating point is discussed in detail elsewhere[16].

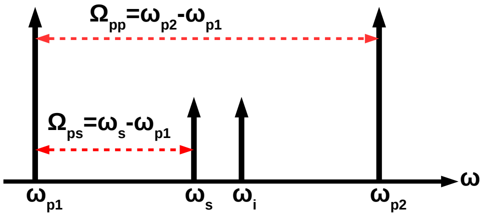

Fig. 4: Mixing of frequencies ω_{p1}, ω_{p2} and ω_s in a third order nonlinear medium generates $\omega_i = \omega_{p1} + \omega_{p2} - \omega_s$, which can be made phase conjugated with respect to the signal.

B. Phase Sensitive Amplification

Generating a phase conjugate to the incoming signal is a critical part of PSA, which can be realized using the process of four wave mixing and an appropriate choice of the generated frequency component. When two pumps at frequencies ω_{p1} and ω_{p2} and a signal at ω_s are given as input into a third order nonlinear medium, an idler wave at a frequency $\omega_{p1} + \omega_{p2} - \omega_s$, which is a conjugate to the input signal, is generated (shown in figure 4) through nonlinear mixing.

As mentioned earlier, we use the nonlinear properties of a semiconductor optical amplifier to achieve phase conjugation. Four wave mixing in SOA, which is responsible for the conjugate generation is modeled by solving the rate equation for the integrated gain [1], given as

$$\frac{dh}{dt} = \frac{g_0 L - h}{\tau_c} - \frac{P_{in}(\tau)}{E_{sat}}[exp(h) - 1], \quad (3)$$

where $h(t) = \int_0^L g(z,t)dz$ is the integrated gain of the amplifier, $g(z,t)$ is the gain experienced by the signal at a specific z along the length(L) of the SOA at a time instant t. g_0 is the small signal gain, decided by the dimensions of the SOA, confinement factor and the carrier density. The explanation of the terms used along with their values used in simulation are listed in Table 1. These values have been chosen to closely resemble those of a practical nonlinear SOA. P_{in} represents the total input power as a function of time.

For a total input field $E_{in}(t)$

$$E_{in} = E_{0p1}e^{i(\omega_{p1}t+\phi_s)} + E_{0p2}e^{i((\omega_{p1}+\Omega_{pp})t+\phi_{p1})} + E_{0s}e^{i(\omega_s+\Omega_{ps})t+\phi_{p2})} \quad (4)$$

The total output field is given by [1]:

$$E_{out} = E_{in}e^{0.5(-\alpha_{int}+h(t)(1-i\alpha))} \quad (5)$$

where E_{0s}, E_{0p1}, E_{0p2} are the amplitudes and $\phi_s, \phi_{p1}, \phi_{p2}$ are the phases of the input fields. Ω_{ps}, and Ω_{pp}, are the frequency separations between pump1 and signal, and pump1 and pump2 repectively. $\alpha_{int}L$ and α are internal loss and linewidth enhancement factor respectively. Equation (3) is solved using a predictor-corrector algorithm, for the input power levels derived from the total input field. From this, fields at various frequencies at the output can be obtained from equation (5) and analyzed.

TABLE I: **Table of parameters used in the numerical simulation of FWM in SOA**

Parameter	Description	Numerical Value
Γ	Confinement Factor	0.35
a	Gain Coefficient	$1.45 \times 10^{-20}m^2$
N_0	Carrier Density at transparency	$0.72 \times 10^{24}m^{-3}$
L	Length of active region	$1mm$
b	Breadth of active region	$1\mu m$
h	Height of active region	$0.18\mu m$
τ_c	Carrier Lifetime for Carrier Density Pulsations (CDP)	$300ps$
P_{sat}	Saturation Power	$4dBm$
α	Linewidth Enhancement Factor	6
α_{int}	Internal Loss	$2000m^{-1}$

1) Modified Phase Matching Condition: Four wave mixing is a *coherent* process where the waves involved follow a definite *phase matching relation*. The phase matching condition for a conventional four wave mixing process is given as [17]

$$\phi_i = \phi_{p1} + \phi_{p2} - \phi_s + \pi/2, \quad (6)$$

where ϕ_{p1} and ϕ_{p2} are pump phases, ϕ_s is the signal phase. However, based on the our simulation results, the phase matching relation for FWM in SOA in the scheme shown in Fig. 4 needs to be modified as

$$\phi_i = \phi_{p1} + \phi_{p2} - \phi_s + \phi_c, \quad (7)$$

where ϕ_c is a phase factor that depends on experimental parameters such as input optical power, SOA current, and the frequency detuning between pumps. This factor is usually missing in conventional HNLF-based four wave mixing, and has its origin on the gain-dependent phase in an SOA. To illustrate the dependence and importance of ϕ_c, we numerically simulate the four wave mixing process in the SOA and extract the evolution of this additional phase factor for different power levels into the SOA. These results are shown in Fig. 5. Similar dependencies are found when the drive current and the detuning between the pumps are modified. The figure also shows the magnitude of the additional phase factor as a function of input power for the case where $\alpha = 0$. It is found to be independent of the pump power for the $\alpha = 0$ case. Thus, the gain-dependent phase can be seen as arising from the linewidth enhancement factor α, which represents the dependence of refractive index and hence gain on the carrier density

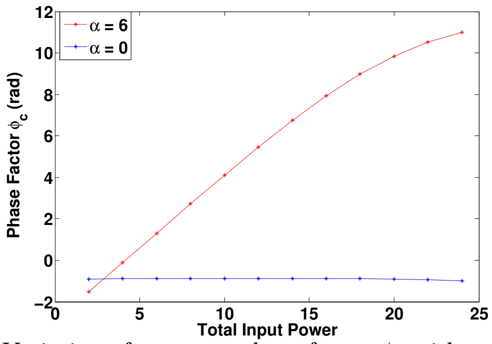

Fig. 5: Variation of constant phase factor ϕ_c with total power input to the SOA.

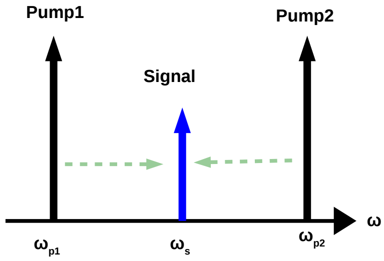

Fig. 6: Four Wave Mixing scheme for PSA: Mixing of frequencies ω_{p1}, ω_{p2} and $\omega_s = \frac{\omega_{p1}+\omega_{p2}}{2}$ produces an idler at frequency ω_s.

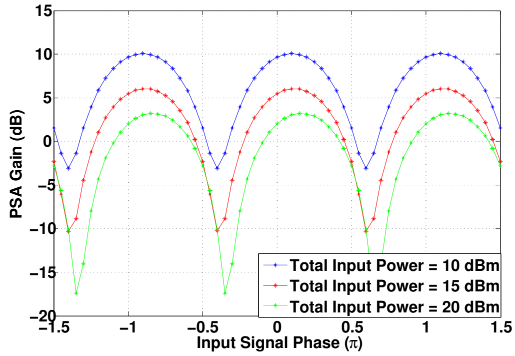

Fig. 7: Phase Sensitive Amplification: Variation of Signal Gain with Input Signal Phase.

in the semiconductor gain material. This effect has been very well incorporated into the numerical model that we have used. For a given set of experimental parameters such as input power, detuning and injection current, the gain dependent phase is a constant and the pump and signal phases should be adjusted so as to satisfy the phase matching condition given in equation (7) rather than equation (6), in order to generate an idler that has its phase conjugated to the signal.

2) Phase Squeezing: The pump and signal frequencies can very well be chosen such that the signal frequency lies exactly in between the pump frequencies, as shown in Fig. 6. This is a special case of the scheme shown in Fig 4, with $\omega_1 = \omega_{p1}$. In such a case, the idler generated through the four wave mixing process would lie at exactly the same frequency as the signal. In other words, the resulting idler combines *coherently* with the signal. If the pumps have conjugate phase characteristics, and satisfies phase matching condition as shown in Eq. 6, a coherent combination of the signal and its *conjugate* idler results in an output signal *squeezed* in phase. This scheme is therefore of great use in regeneration of noisy BPSK modulated signals, where the two "allowed" phases are 0 and π.

The characteristic feature of phase sensitive amplification is the phase-dependent gain, quantified through the gain extinction ratio (GER). As the signal phase is swept between 0 and 2π, depending on the phase matching condition given in Eq 6, the power generated in idler changes, thus changing the PSA gain. GER is defined as the ratio of the maximum and minimum gain experienced by the signal. The operating point for phase squeezing is chosen after studying the variation of the Gain Extinction Ratio (GER) as function of experimental parameters such as input power, frequency detuning and injection current. The GER correlates to the extent of squeezing that can be obtained — intuitively, a larger difference in gain seen by phase ϕ and $\phi + \frac{\pi}{2}$ would imply better squeezing, as can be seen from Fig. 1. Fig. 7 shows the dependence of the gain the signal sees — the PSA gain — as function of input signal phase. Notice that the signal phases for maximum and minimum gains are $\pi/2$ apart — consistent with the idea that one quadrature experiences a higher gain than the other, as demonstrated in figure 1.

The GER is found to change with the input signal power. As the input power increases, the gain is saturated. Thus, the peak gain observed would reduce. Figure 8 shows the dependence of gain extinction ratio on the *total* power input to the SOA. The GER is found to remain constant for a range of input signal power levels. The trend seen is consistent with what has been reported in [18]. The input power for which the gain extinction ratio is the largest was chosen for the operating point.

Fig. 9 demonstrates the results of our numerical simulations. The constellation plot shows a signal modulated with BPSK at 10 Gbps, with high phase noise at the input to the PSA. The output is clearly seen to have a lower phase noise, although with a higher amplitude noise as a trade-off. This is consistent with the uncertainty principle, the reduction in phase noise is accompanied by an increase in amplitude noise. However, it must also be remembered that in the specific context of phase modulated signals, the phase performance is more critical.

The phase squeezing performance of the system is also shown in the phase transfer function plot in Fig. 10. The instantaneous phase at the input, which fluctuates

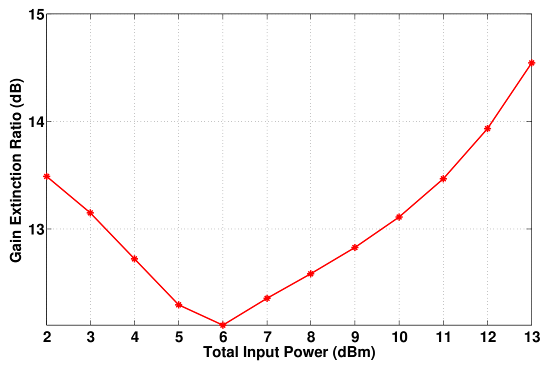

Fig. 8: Operating Point for the PSA stage: Gain Extinction Ratio (GER) as function of Total Input Power.

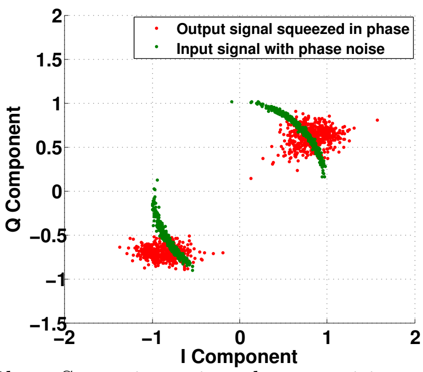

Fig. 9: Phase Squeezing using phase sensitive amplification

due to phase noise, is plotted on the x-axis, and the instantaneous output phase is plotted on the y-axis. The plot shows that for a rather large spread in the input phase, the spread in output phase is much smaller; demonstrating the effect of phase squeezing.

Notice that although the PSA is able to squeeze phase noise, there is certainly some conversion to amplitude noise. It is still important to reduce the amplitude noise in a multi span link.

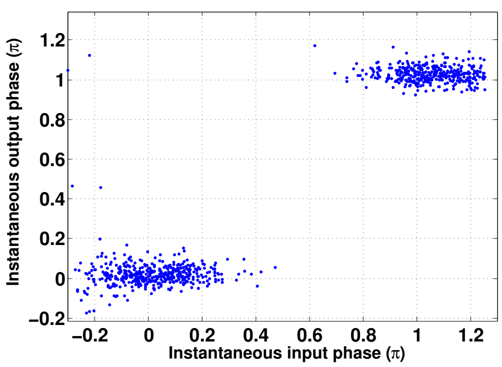

Fig. 10: Phase Squeezing using phase sensitive amplification: Transfer function plot of output phase vs input phase

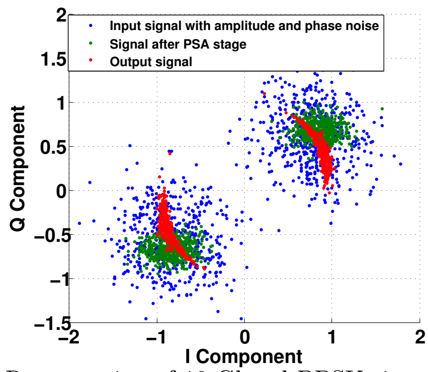

Fig. 11: Regeneration of 10 Gbaud BPSK signals: PSA+IL

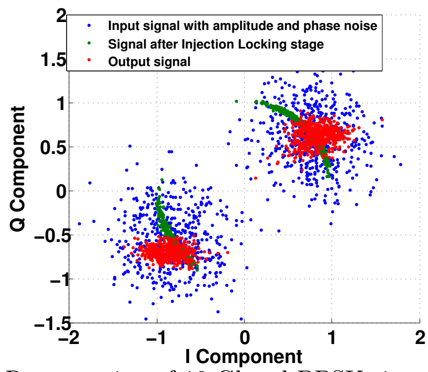

Fig. 12: Regeneration of 10 Gbaud BPSK signals: IL+PSA

III. Regeneration Scheme: Combination of PSA and IL — Results and Discussion

The central idea of our work has been to show, via numerical simulation, that a combination of the PSA and injection locking can be utilized to regenerate phase modulated signals in long-haul optical communication systems. Conventional amplitude suppression schemes involve the use of saturable absorbers, which could be lossy. The proposed arrangement would *actively* control phase and amplitude noise, as opposed to the *passive* action that the saturable absorbers provide. The injection locking scheme is very useful in actively suppressing amplitude noise, while phase sensitive amplification enables squeezing in phase. Therefore, cascading the two of these stages and sending in a noisy signal can utilize the capabilities of both the stages to get a less noisy signal at the output.

Results of our numerical simulations are shown in figures 11 and 12. Figure 11 shows the results of regeneration of BPSK data where PSA is performed first, followed by injection locking (this is denoted as PSA+IL), while Fig. 12 shows the case where the sequence of operation is reversed (denoted as IL+PSA). The input data to both the systems were identical — with BPSK data at 10

Gbps and an $OSNR$ of 10 dB. In IL+PSA, shown in Fig. 11, the simulation results indicate quantitatively that the data at the output of both the stages has an phase noise variance improvement factor (defined as the ratio of the input noise variance to the output noise variance) of about 15 while the amplitude noise variance improvement factor is 5, resulting in an overall improvement factor of 75. The overall improvement factor is defined as the product of phase noise and amplitude noise improvement factors. On the other hand, for PSA+IL, shown in Fig. 12, we report an improvement in phase noise variance by a factor of 4, amplitude noise variance improvement factor of 40, resulting in an overall improvement by a factor of 160. Thus, the overall performance is better for the PSA+IL scheme. However, one must note that this sequence is specific to the set of parameters chosen for the two subsystems. Nevertheless the underlying principle that the order in which these operations are carried out is important, remains unchanged. Both of these stages have been tuned to their optimized operating points in these simulations. The two sub systems are independent of each other and hence have been optimized separately. Given that the parameters chosen are close to actual experimental parameters, this work indicates that a practical system can be built that combines the advantages of injection locking and phase sensitive amplification for the purpose of signal regeneration. The scheme can be extended to M-PSK with appropriate choice of idler for PSA [19].

IV. Conclusions

In this paper, we study the phase sensitive amplification process and injection locking in the context of regeneration of phase modulated signals through numerical simulations. Each of these processes are simulated independently. The conditions for detuning and injection ratio to achieve a stable locking is derived by solving the dynamic rate equations for electric field and population density in the slave laser. We also report a modified phase matching relation for four wave mixing in SOA for the first time, considering the role of gain dependent phase in the process. We demonstrate the conditions for PSA in SOA, considering the modified phase matching conditions. We further simulate the comprehensive amplitude and phase noise noise reduction system with the objective of finding the optimal sequence of operation. For our simulations, with BPSK data, PSA+IL scheme gives us better overall noise performance.

ACKNOWLEDGMENT

We would like to gratefully acknowledge the Department of Science and Technology, Government of India for funding this research.

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