Optical Amplitude Multiplexing through Parametric Amplification: An Analysis for the Idler Signal

A. L. A. Costa, J. D. Marconi, F. R. Barbosa, E. Moschim
School of Electrical and Computer Engineering/ Institute of Physics
University of Campinas-UNICAMP
Campinas, Brazil
alcosta@dsif.fee.unicamp.br
jdmarconi1@gmail.com
felipe@dsif.fee.unicamp.br
moschim@dsif.fee.unicamp.br

M. L. F. Abbade1, Member, IEEE
School of Electrical Engineering
PUC-Campinas
Campinas, Brazil
abbade@puc-campinas.edu.br

Abstract — **Recently a new technique that used parametric amplification in optical fibers to combine two binary signals into a single quaternary amplitude-shift keying (4-ASK) signal, at frequency of signal to be amplified, was proposed. In this paper, other new technique with use of parametric amplification, also to combine two binary signals into a single quaternary amplitude-shift keying (4-ASK) it is proposed, however, the 4-ASK signal will be generated at idler frequency. We also develop a theoretical model to predict the power level distribution of the 4-ASK signals as a function of the extinction ratios of the input binary signals. Computer simulation results agree with the predictions of this theoretical model within a 1.3 dB margin. Finally, was also performed some simulation to compare the propagation between 4-ASK idler signal with 4-ASK probe signal. This technique could be applied to optically generate optical packets.**

Keywords— Optical signal processing, parametric amplifiers (PA), quaternary-amplitude shift keying (4 - ASK).

I. INTRODUCTION

The detrimental aspects caused by fiber non-linear effects, on the transmission of signals through optical links, were thoroughly investigated in the past decades. For example, the influence of four-wave mixing (FWM) and modulation instability in wavelength division multiplexing (WDM) systems was reported in [1, 2]. In recent years, however, the beneficial properties of fiber non-linearities have also attracted a lot of interest. In particular, such properties may be used in the fabrication of all-optical devices that: a) remove unnecessary electro-optical and opto-electronic conversions in optical communications systems [3], b) perform signal processing in the optical domain [4], and c) consume lower energy than its electronic counterparts [3].

Another important field of research is the investigation of new modulation formats, which are able to provide higher spectral efficiencies than the traditional on-off keying (OOK) modulation and, thus, could be used to enhance the utilization of the presently deployed fiber infrastructure. Among several multi-lievel modulation schemes, quartenary amplitude-shift keying (4-ASK) presents the advantage of combining a spectral efficiency which is twice as high as the one provided by OOK which a bit error rate that is considerably lower than modulation schemes with a higher number of power levels [5]. Following both of these trends, recent work [6-7] suggested that (nonlinear) parametric amplification may be used to multiplex two binary signals into a single 4-ASK one.

In particular, such amplitude multiplexing was perfomed by utilizing a modulated signal, at the optical carrier f_s and a modulated pump at f_P.

However, it is important to note that the FWM interaction between these signals also generates an idler signal at $2f_P - f_S$. In this work, we present a theoretical model that indicates that, under certain circumnstances, a 4-ASK signal should also be present at the idler signal. Moreover, the power level distribution of this 4-ASK signal is different from the one for the signal at f_S (i.e., the quaternary signal at f_i is not a wavelength converted version of the signal at f_S). We also perform simulations to evaluate the performance of such signal and compare its performance with the one provided by the signal at f_S. To the best of our knowledge, this is the first time that such analysis is presented in literature.

This work is organized in the following way. In Section II the theoretical principles of parametric amplification are addressed. In section III theoretical principles of the proposal of this work are shown; computer simulations will test the theory presented in Section IV. Finally, in Section V will be shown the final conclusions.

II. CONVENTIONAL PARAMETRIC AMPLIFICATION

Parametric amplification in primary application is used to compensate losses in optical links. In fact, a high power pump signal (cw), at frequency f_P, and the signal to be amplified, at f_S , are coupled and propagated through in a specially designed optical fiber, with a length L. The amplification bandwidth is [8]:

$$f_P - \frac{1}{2\pi}\sqrt{\frac{2\gamma P_P e^{(-\alpha L/2)}}{|\beta_2|}} \le f_S \le f_P + \frac{1}{2\pi}\sqrt{\frac{2\gamma P_P e^{(-\alpha L/2)}}{|\beta_2|}} \qquad (1)$$

where P_P is the pump power, and γ, β_2, and α are, respectively, the nonlinear coefficient, group velocity dispersion parameter and the atennuation of the fiber. The gain offered by the probe signal is given by [9]:

$$G_P = \frac{P_S(L)}{P_S(0)} = 1 + \left(\frac{\gamma P_P}{g}\sinh(gL)\right)^2 \qquad (2)$$

where $P_S(0)$ and $P_S(L)$ are respectively the signal input and output powers of the parametric amplifier, and g is the parametric gain described in [9]. In additional to gain, parametric amplification, generates a new signal component at $f_i = 2f_P - f_S$. This signal is known as idler is caused by four wave mixing process. It is gain factor may be evaluated from [9]:

$$G_i = \left(\frac{\gamma P_P}{g}\sinh(gL\ )\right)^2 \qquad (3)$$

III. PARAMETRIC AMPLIFICATION AMPLITUDE MULTIPLEXING AT IDLER FREQUENCY

The principle of the technique proposed in [6], called parametric amplification amplitude multiplexing (PAAM), is the same as parametric amplification; however, both the pump and the signal are modulated in a binary manner, in amplitude, and have the power of "0" intentionally shifted a non-null value. Under this aproach and following (2), we verify that the pump provides two gains to the probe signal, G_P^0 and G_P^1, depending on the transmission of bit "0"or "1", respectively.

There, the level of bit "0"of the signal at f_S will experience both of these gains; this will happen for the level of bit "1" of the siganal at f_S. Hence, the signal at the output of optical band-pass filter (OBPF) will become a quartenary signal containing information carried by the pump (at f_P) and probe signal (at f_S). This subject was already presented in [6].

Hower, in the present work, we note that the idler signal may also experience this binary-to-quartenary amplitude convertion. In fact, according to (3) the idler signal will experience two gains given by:

$$G_i^{0,1} = \left(\frac{\gamma P_P^{0,1}(0)}{g^{0,1}} sinh\left(g^{0,1} L\right) \right)^2 \qquad (4)$$

$P_P^0(0)$, $P_P^1(0)$, g^0, g^1 are power and parametric gain of bits "0" and "1" at input the parametric amplifier.

Similarly, we can define the powers of the bits "0" and "1" from signal also at input parametric amplifier as $P_S^0(0)$ and $P_S^1(0)$. Therefore, it is possible to show that the output powers at frequency f_i take the following values:

$$P_{out}^{00} = G_i^0 P_S^0(0) \qquad (5a)$$

$$P_{out}^{01} = G_i^0 P_S^1(0) \qquad (5b)$$

$$P_{out}^{10} = G_i^1 P_S^0(0) \qquad (5c)$$

$$P_{out}^{11} = G_i^1 P_S^1(0) \qquad (5d)$$

where P_{out}^{ij} indicates the output power when, at the fiber input, the pump carries bit *i* and the probe signal transmits bit *j*. Equations (5a)-(5d) show the dependence of 4-ASK idler signal generation with the parametric amplification. Fig.1 illustrates conceptually generation of 4-ASK signals in both frequency, f_S, of probe signal, as in f_i, of idler signal.

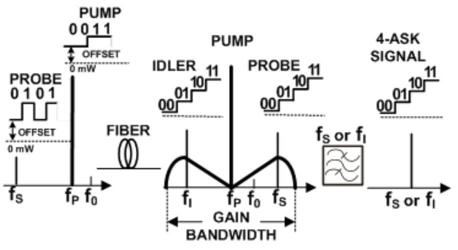

Fig.1. Generation conceptual of 4-ASK signals at f_S, and f_i

Then, designating the probe, pump factor extinction ratios (ERs), respectively, by $r_S = P_S^1(0)/P_S^0(0)$, $r_P = P_P^1(0)/P_P^0(0)$, idler amplification ratio as $r_{G_i} = G_i^1/G_i^0$ and assuming that $G_i^0 P_S^1(0) > G_i^1 P_S^0(0)$ (i.e., if $P_{out}^{10} > P_{out}^{01}$), the relative ERs (RERs) between two each consecutive power levels are given by:

$$\rho_{low} = P_{out}^{01}/P_{out}^{00} = P_S^1(0)/P_S^0(0) = r_S \qquad (6a)$$

$$\rho_{int} = P_{out}^{10}/P_{out}^{01} = \left(G_i^1/G_i^0\right)\left(P_S^0(0)/P_S^1(0)\right) = r_{G_i}/r_S \qquad (6b)$$

$$\rho_{up} = P_{out}^{11}/P_{out}^{10} = P_S^1(0)/P_S^0(0) = r_S \qquad (6c)$$

Otherwise ($G_i^0 P_S^1(0) \le G_i^1 P_S^0(0) \Leftrightarrow P_{out}^{10} \le P_{out}^{01}$), the RERs become:

$$\rho_{low} = P_{out}^{10}/P_{out}^{00} = \left(G_i^1/G_i^0\right)\left(P_S^0(0)/P_S^0(0)\right) = r_{G_i} \qquad (7a)$$

$$\rho_{int} = P_{out}^{01}/P_{out}^{10} = \left(G_i^0/G_i^1\right)\left(P_S^1(0)/P_S^0(0)\right) = r_S/r_{G_i} \qquad (7b)$$

$$\rho_{up} = P_{out}^{11}/P_{out}^{01} = \left(G_i^1/G_i^0\right)\left(P_S^0(0)/P_S^0(0)\right) = r_{G_i}, \qquad (7c)$$

From (4), it may be noted that the idler gain ratio $r_{G_i} = G_i^1/G_i^0$ is controlled by the pump extinction rate $r_P = P_P^1(0)/P_P^0(0)$.

The quartenary signal suggested by (5) seems to be a consequence of the FWM interaction between the probe and pump signals. In fact, in the very beginning of the fiber such intereaction must generate a " copy" of the probe signal into the idler frequency. This new signal component must, then, be amplified by the two pump power levels. It is also important to note that the power level distribution at the idler signal (which is the focus of our present work) is diferent from the one of the probe signal (which was analyzed in [6]).

IV. Simulation Results and Discussion

To evaluate the new technique proposed in this article, some simultions were performed in a commercially available software, where fiber propagation is obtained by solving the nonlinear Schrödinger equation through a split-step Fourier algorithm. The simulation scheme is illustraded in Fig. 1a. a 10 Gbits/s 2-ASK pump signal with average power of 80 mW, at f_P= 192.50 THz, and a 10 Gbits/s 2-ASK probe signal with average power of 1 mW at, f_S= 192.10 THz, were coupled and propagated through a 3-km long highly-non linear dispersion shifted fiber (HNL-DSF) with α= 0.83 dB/km, γ= 9.1 (W.km)$^{-1}$, λ_0 = 1556.0nm (192.66 THz) with variation $\Delta\lambda_0$= ± 5nm and dispersion slope S_0 = 0.015 ps/nm^2/km. We assumed that both signals were synchronized and in the same state of polarization (SOP). An additive Gaussian white noise with power spectral density of 10^{-17} W/Hz was inserted at the fiber input to simulate the noise present in real-world applications (This is not shown in Fig. 2a). The an optical band-pass filter (OBPF) was utilized to select the signal at f_i.

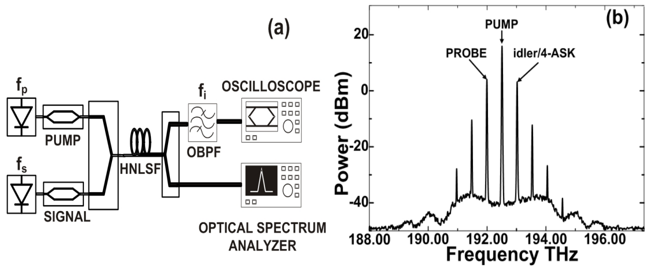

Fig.2. (a) Simulation setup and (b) Power Spectrum at the HNL-DSF output.

The output spectrum at the HNL-DSF output is shown in Fig. 2b. The idler signal, which is the focus of this work, is generated at $f_i = 2f_P - f_S$ = 192.9 THz. The presence of MI is observed because the pump is placed in the anomolous dispersion regime. It is important to mention that, since the probe signal is not placed at the region of maximum MI gain, idler is not experiencing the maximum gain that could be provided by the pump. Morevover, spurious signals at frequencies $2f_S - f_P$ = 191.7 THz and $3f_P - 2f_S$ = 193.3 THz should deplete the pump, the probe, and the idler signals.

In Fig. 3, we show (a) the pump and (b) probe signals at the fiber input, and (c) the 4-ASK-idler signal at the OBPF output, for r_S= 3 dB and r_P= 3 dB ($r_{G\ i}$= 6.54 dB). As expected form our previous model, it is clear that a quaternary signal, with very well defined power levels, is present at the idler frequency.

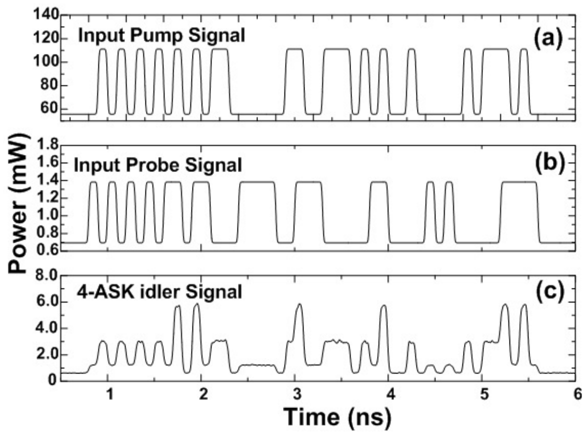

Fig.3.Binary data at (a) f_P and (b) f_S; (c) 4-ASK signal at f_i.

As indicated by (6) and (7), the power level distribution of the 4-ASK signal at f_i depends on r_{Gi} and r_S. To verify the validity of this behavior, we simulated eye diagrams r_p = 3dB (r_{Gi} = 6.5dB) and (a) r_S = 3dB, (b) r_S = 6.5dB and (c) r_S = 9.0dB. The diagram from Fig. 4a, describes clearly the situation of (6), where $P_{out}^{10} > P_{out}^{01}$. The opposite situation, $P_{out}^{10} \le P_{out}^{01}$, occurs for Fig. 4c, where (7) should hold. In Fig. 4b occurs a degenerated case, where $r_S = r_{Gi}$= 6.5dB; in this case, it is impossible to recover the originals signals from signal generated at the idler frequency.

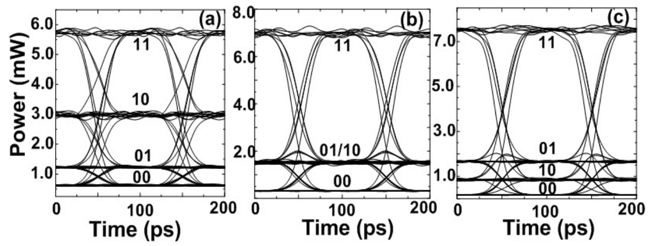

Fig.4: Eye diagrams for r_P = 3dB (r_G = 6.5 dB) and r_S = (a) 3.0, (b) 6.5, and (c) 9.0 dB.

Also, to evaluate the relative RERs between two consecutive power levels, we performed some tests where r_S and r_{Gi} are varied, them we compared the RER's obtained in simulation ith the ones predicted by (6) and (7).

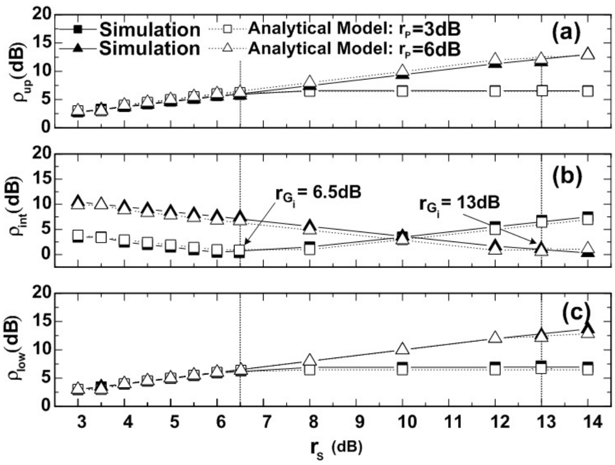

Fig.5 RERs of the 4-ASK as a function of r_S.

In these tests we adopted two r_P values(r_P = 3 and 6 dB), which correspond to r_{Gi} =6.5 and 13 dB respectively. As mentioned before r_{Gi} is controlled by r_P. The probe signal ER, r_S was varied in the range from 3 to 14 dB, as Illustrated in Fig5.

In Fig. 5a and 5b, note that ρ_{up} and ρ_{low}, increasing in proportion to the value of r_S, while ρ_{int} decreases. This behavior occurs until r_S reaches the same value of r_{Gi}, thus, obeying the rule previously presented in (6) (i.e $P_{out}^{10} > P_{out}^{01}$). These points are shown in Fig. 4b, indicated for $r_S = r_{Gi}$= 6.5, 13 dB and therefore ρ_{int} is 0dB, note that for these cases has degenerate case shown previously in Fig. 4b. From the points mentioned above, ρ_{up} and ρ_{low}, become constant, always assuming the r_{Gi} value, while ρ_{int} will now grow proportionately to r_S, this behavior is consistent with (7) (i.e $P_{out}^{10} \le P_{out}^{01}$). These results were compared with the analytical solutions of (6) and (7), and reveal a quite good agreement between these aproches is of only 0.83 dB.

This difference is partially related with the variaton of wavelength of zero dispersion and depletion, which, was not considered in the analytical solution, but it was taken account in our simulations.

Still with the aim of evaluating RERs, in Fig.6, we adopted r_S = 3 and 6dB, and r_P was varied from 3 to 14 dB (corresponding to r_{Gi} = 6.5 and 29.61 dB).

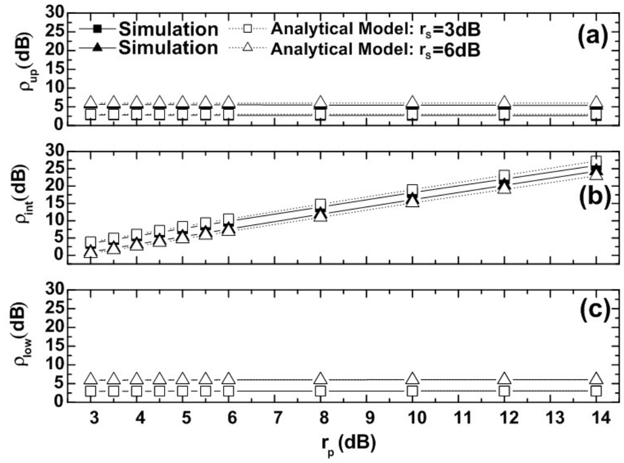

Fig. 6: RERs of the 4-ASK as a function of r_P.

In this case, since r_{Gi} is grater than r_S , only (6) holds. For this reason ρ_{up} and ρ_{low} keep their values irrespectively of r_P. Moreover, ρ_{int} increase linearly with the increase of r_P. Again, it is observed a good agreement between simulations amd theoretical model(with in a 1.3 dB of error margin).

Finally we perform a comparison of the eye diagrams of the quaternary probe signal and the quaternary idler, after propagation through a network. Fig.7 shows: (a) the idler signal with r_S = 6dB and r_p =1.4dB (r_{Gi} = 3dB), and (b) the probe signal with r_S = 6dB and r_p =1.8dB (r_G = 3dB), both before propagation $(\rho_{up} = \rho_{int} = \rho_{low} = 3dB)$.

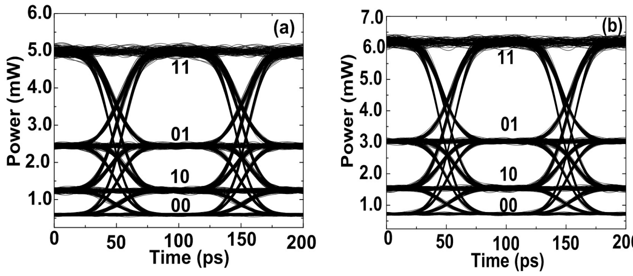

Fig.7. Input Eye diagrams for propagation evaluation (a) 4-ASK idler signal and (b) 4-ASK probe signal.

The setup shows in Fig.8 was used to simulate the propagation. The attenuators of 3.6 dB and 4.5 dB were used to ensure that both, the idler and the probe signal, enter into the link with the same optical power (i.e. 0 dBm).

The link consists of 50 km of standard single mode fiber. For dispersion compensation were used 8.98 km and 9.41 km of dispersion compensation fiber (DCF) for the idler and the probe signal, respectively. Then each optical wave was pre-amplified and launched into a 3dB coupler to split the optical power in two parts. On part was used for Bit Erro Rate (BER) characterization and the other was sent through another link. The analysis of the degradation was limited to links with a maximum length of 300 km.

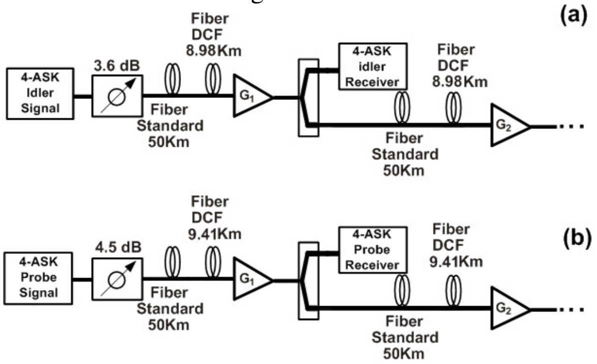

Fig 8.Propagation setup (a) 4-ASK idler and (b) 4-ASK probe.

The BER for both 4-ASK signals at f_i, f_S and f_P (pump) are calculated by the equations:

$$BER_{PROBE} = \frac{1}{3}\left[Q\left(\frac{i_{10}-i_{00}}{\sigma_{00}+\sigma_{10}}\right)+Q\left(\frac{i_{01}-i_{10}}{\sigma_{01}+\sigma_{10}}\right)+Q\left(\frac{i_{11}-i_{01}}{\sigma_{11}+\sigma_{01}}\right)\right] \quad (8a)$$

$$BER_{IDLER} = \frac{1}{3}\left[Q\left(\frac{i_{10}-i_{00}}{\sigma_{00}+\sigma_{10}}\right)+Q\left(\frac{i_{01}-i_{10}}{\sigma_{01}+\sigma_{10}}\right)+Q\left(\frac{i_{11}-i_{01}}{\sigma_{11}+\sigma_{01}}\right)\right] \quad (8b)$$

$$BER_{PUMP} = Q\left(\frac{i_{01}-i_{10}}{\sigma_{01}+\sigma_{10}}\right) \quad (8c)$$

note that the BER of the pump is calculated indirectly from the levels of the quaternary eye diagrams of the idler and the signal.

Fig. 9 illustrates the BER for both, the idler and the probe signal. The performance between them is very similar. They achieved a BER = 1.10^{-9} after propagation through a distance of 300 km.

Fig. 10 presents the BER of pump calculated with Eq.8(c) by using the quaternary eye diagrams of idler and signal. They show a similar performance after a distance propagation of 200 km. From that point on the BER performance of the pump calculated from the signal becomes worse. This can be explained considering that the efficiency of the 4-ASK at the idler frequency is smaller than the signal gain (Eqs. (2) and (3)).

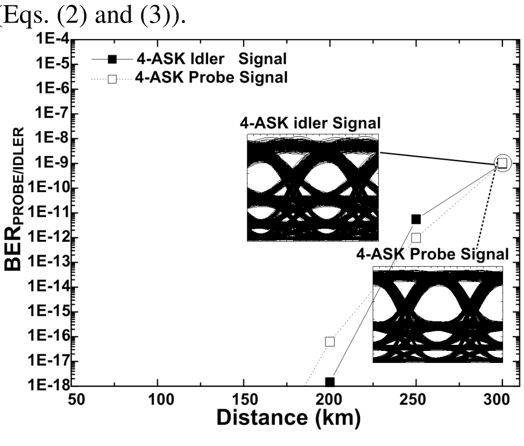

Fig.9. BER evaluation of probe and idler as a function of distance.

Is important to mention that the purpose of these simulations is presents a comparison between the performance of the quaternary optical signals at f_i and f_S under the same propagation conditions, and not to obtain the best transmission performance. For instance, from Fig.2b. it is possible to verify that probe signal is not placed in the region of maximum parametric gain. Then re-tuning the signal to that region of higher gain could be possible to achieve longer propagation distances[7].

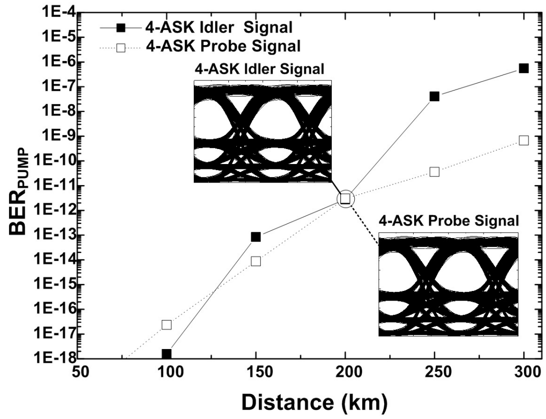

Figure 10 BER evaluation of pump as a function of distance.

It is possible to recover the information contained in the original binary signals from the quaternary level system by using a proper electronics after the photo-detection. This electronics should be able to interpret some logical rules. For instance, for the case of Fig.(4a), where $P_{out}^{10} > P_{out}^{01}$, a bit 1 should be interpreted for pump if power levels detected are those corresponding to the "10" and "11" levels, otherwise the bit 0 must be interpreted. For the case of Fig.(4c), $P_{out}^{10} \leq P_{out}^{01}$, the rule mentioned above must be inverted. All-optical solutions are also possible, as the one presented in [10].

V. Conclusion

In this work, we investigated a new technique for multiplexing two binary signals into a single quaternary one. The technique is based on conventional parametric amplification, but it uses a modulated pump; in addition to this, the powers of the bit 0 of the pump and probe signals are offset to a non-null value. In particular, we analyzed the performance of the quaternary signal generated at the idler frequency, $f_i = 2f_p - f_s$, whereas another work [6] analyzed the performance of the singal at f_s.

Our results suggest that the theoretical model we developed is able to predict the powers of the quaternary signal within a rather good, 1.3 dB, margin (comparison between theory and simulations). Moreover, we also found that the propagation distance obtained by the quaternary signal generated at the idler is similar to the one achieved for the signal at f_P. A possible continuation of this work could encompass an experimental analysis.

Finally, we should observe that the technique investigated in this work may be used for some importante applications, such as labeling optical packets[6] and performing digital-to-analog conversion [11].

Acknowledgments

The authors thank FAPESP and CNPq for funding this work under process 574017/2008-9, 309031/2008-7, 142270/2007-5 and 2008/5787-2. The authors also thank Dr. Dr. E.A.M. Fagotto for fruitful discussions.

References

[1] S. Song, C. T. Allen, K. R. Demarest, and R. Hui, "Intensity-Dependent Phase-Matching Effects on Four-Wave Mixing in Optical Fibers", *J. Lightw. Technol*, vol. 17, no. 11, pp. 2285-2290, Nov. 1999.

[2] D.F. Grosz, J.M. Cha´vez Boggio and H.L. Fragnito, "Modulation instability effects on three-channel optically multiplexed communication systems", *Optic.Commun*, no 171, pp. 53–60, 1999.

[3] K. Hinton, et al.: Switching Energy and Device Size Limits on Digital Photonic Signal Processing Technologies, IEEE J. Select. Topics in Quantum Electron.,vol. 14. no. 3 pp 938-945, Jun. 2008.

[4] S. Boscolo and S. K. Turitsyn "Recent Developments in All-Optical Nonlinear Data Processing" presented at *European Conference on Optical Communication* , vol. 4, pp.63-66, Sep 2008, Brussels, Belgium. Digital Object Identifier: 10.1109/ECOC.2008.4729395

[5] S.Walklin, J. Conradi, "Multilevel Signaling for Increasing the Rech of 10Gbit/s Lightwave Systems", J. Lightwave Tech,.pp2235-2248, Nov.1999.

[6] M.L.F. Abbade, A.L.A. Costa, F.R. Barbosa, F.R. Durand, J.D. Marconi, E. Moschim, "Optical Amplitude Multiplexing Through Parametric Amplification in Optical Fibers" *Optics Comm,* no 283, pp. 454–463, 2010.

[7] M. L. F. Abbade1, J. D. Marconi, A. L. A. Costa, F. R. Barbosa, E. Moschim, H. L. Fragnito "All-optical Generation of Quaternary Amplitude-Shift Keying Signals through Parametric Amplification" accepted on International Conference on Transparent Optical Networks, 2010.

[8] G.P. Agrawal: Nonlinear Fiber Optics, Third Edition., New York: Academic Press, 2001

[9] J. Hansryd, P. A. Andrekson, M. Westlund, J.Li and P. Hedekvist "Fiber Based Optical Parametric Amplifiers and Their Applications IEEE Jour Of Selec. Top. in Quant. Electr., Vol 8, no. 3, May/June 2002.

[10] E.A.M. Fagotto, M.L.F. Abbade, "All-optical demultiplexing of 4-ASK optical signals with four-wave mixing optical gates" *Optics Comm,* no 283, pp 1102–1109, 2010.

[11] T. Nishitani, et al.: All-optical digital-to-analog conversion using pulse pattern recognition based on optical correlation processing, Opt. Express., vol. 13. no. 2512. pp.10310-10315, Dec. 2005.