Optical Multiplexing through FWM in Highly Nonlinear Fibers: A Novell Device

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Abstract- **This paper proposes a technique to accomplish optical multiplexing through FWM interaction. It is theoretically argued how two OOK WDM channels may be multiplexed into a single optical ASK-4 channel. Simulation results corroborate theoretical expectations. It is also presented an analysis for optimal level detection and simulations for optical ASK-4 transmission through different kinds of fiber. The technique presented is in accordance to some recent attempts to increase spectral efficiency and is appropriated for operating in modern all-optical networks.**

I. Introduction

Popularization of data communications, digitized voice and video services is increasingly demanding higher bit transfer rates. In the last decade, Wavelength Division Multiplexing (WDM) technology has successfully been used to supply this need [1], pushing commercial systems capacity to Tbit/s in a single fiber [2]. However, this achievement requires full Erbium Doped Fiber Amplifier (EDFA) bandwidth utilization, with a channel spacing that borders filtering performance and becomes strongly restricted by fiber nonlinearities impairments [3].

Literature [4] points out two main strategies that may allow further increase on fiber capacity: increasing optical amplifier bandwidth and improving spectral efficiency of WDM signals. The latter may be achieved using technologies like polarization interleaving multiplexing, multi-wavelength stabilization, or utilizing new codification schemes [4]-[8] in spite of traditional On-Off Keying (OOK).

Present work focuses on this last possibility, considering ASK-4 codification signals. It suggests that these signals may be optically generated from the Four Wave Mixing (FWM) [9]-[13] interaction between two offset OOK WDM channels. Organization is as follows. Section II describes basics concepts of FWM and presents the principles of the proposed optical multiplexing technique [14]. Section III discusses optimal level spacing in optical ASK-4 coding. Simulation results are exhibited in Section IV, where transmission of optically multiplexed signals is considered for three different kinds of commercial fibers. Finally, possible applications for the proposed technique and conclusions are pointed out in Section V.

II. Optical Multiplexing Through FWM

When two main optical channels co-propagate through single-mode fibers, nonlinearities generate sideband signals located at frequencies f_- and f_+ [9]:

$$f_- = 2f_1 - f_2 \text{ and} \tag{1a}$$

$$f_+ = 2f_2 - f_1 , \tag{1b}$$

with f_1 and f_2 ($f_1 < f_2$) standing for the optical carriers frequencies of the main channels. This is a degenerated case of the Four-Wave Mixing phenomenon, which has been widely studied in literature [9]-[13].

If the main channels are weakly depleted, the generated channels receive an optical power that can be estimated from [15], [16]:

$$P_- = \eta\gamma^2 P_1^2 P_2 \exp(-\alpha L)\left[\frac{1-\exp(-\alpha L)}{\alpha}\right]^2 \tag{2a}$$

and

$$P_+ = \eta\gamma^2 P_1 P_2^2 \exp(-\alpha L)\left[\frac{1-\exp(-\alpha L)}{\alpha}\right]^2 , \tag{2b}$$

where P_1, P_2, P_-, and P_+ are, respectively, the optical power of the channels at f_1, f_2, f_-, and f_+, L is the fiber length, α is the fiber attenuation, and γ is the fiber nonlinear coefficient. FWM generation efficiency, η, and co-propagating signal phase mismatch, Δk, are given by:

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta k^2}\left\{1 + \frac{4\exp(-\alpha L) sin^2(\Delta k L/2)}{[1-\exp(-\alpha L)]^2}\right\} \tag{3}$$

and

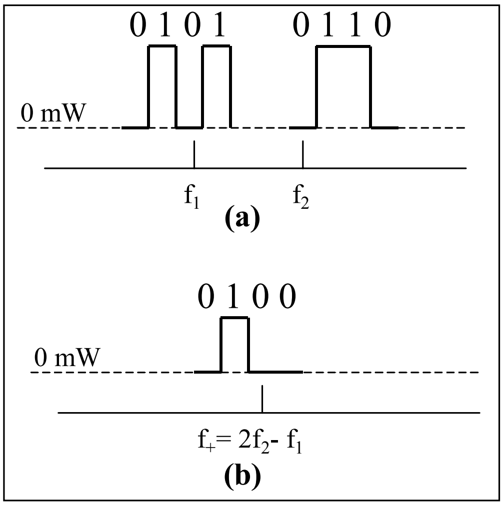

Fig. 1. (a) Two traditional OOK signals being transmitted in a 2-channel WDM system. Words 0101 and 0110 are carried out, respectively, by f_1 and f_2. (b) FWM interaction between signals at f_1 and f_2, signal generated at f_+ is non-null only when both channels carry a bit 1.

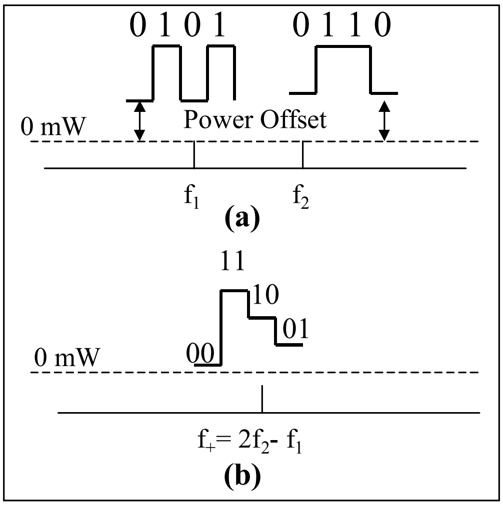

Fig. 2. (a) Two offset OOK signals being transmitted in a 2-channel WDM system. Words 0101 and 0110 are carried out, respectively, by f_1 and f_2. (b) FWM interaction between signals at f_1 and f_2, signal generated at f_+ gives rise to an ASK-4 signal.

$$\Delta k = \frac{2\pi\lambda_k^2}{c}(\Delta f)^2\left[D(\lambda)+\frac{\lambda_k^2}{c}\Delta f\, S(\lambda)\right] \qquad (4)$$

with $\Delta f = f_2 - f_1$, and the wavelength dependent fiber dispersion and dispersion slope represented, respectively, by $D(\lambda)$ and $S(\lambda)$. For clarity reasons, (4) is not taking into account phase matching intensity-dependence [17].

From (2) it is obvious that ideal OOK (On-Off Keying) codification will lead to a null power, $P_{+(-)}$, whenever one of the main channels transmits a bit 0. Figure 1 illustrates power levels observed at f_+ when the words 0101 and 0110 are carried out, respectively, at frequencies f_1 and f_2. It is assumed that the bits maintain time correlation through propagation, which can be achieved for fiber lengths sufficiently smaller than the walk-off length [9], [18]. A similar result would be obtained for power levels observed in f_-.

However, in more general codification schemes, it is physically reasonable to admit that the generated channels will carry information from both signals traveling at frequencies f_1 and f_2.

In particular, if the main channels are codified with a non-zero power to represent bits 0 and with a higher power to represent bits 1, equations (2) predict that generated channels might assume four different levels. These four levels are consequence of the bit combinations (00, 01, 10, and 11) that may be carried out by the main channels and characterize an ASK-4 codification. Figure 2 is analogous to Figure 1, but undertakes the offset of bit 0 power level.

This discussion suggests that optical fibers may be used as optical multiplexers [14]. The idea is as follows. After offsetting power of the main optical channels (f_1 and f_2), they could be propagated through a fiber length inside an optical node until one of the generated signals (for example, at f_+) reaches a desirable power. This ASK-4 signal could then be selected (signals at f_1, f_2, and f_- being filtered) and sent out to next optical node. As this signal presents, approximately, the same bandwidth of the main channels and the double of information, spectral efficiency is increased.

Equations (2) and (3) point out that higher nonlinear parameters and low chromatic dispersion increase the power generated by FWM. Consequently, the proposed strategy could be improved by the utilization of High Nonlinear Dispersion Shifted fibers [19]. The proposed optical multiplexer is schematized in Figure 3.

III. Optical ASK-4 Optimal Level Spacing

Assuming that signal extinction ratios carried on f_1 and f_2 are, respectively, ξ_1 and ξ_2, equations (2) can be used to estimate the ASK-4 signal optical power levels, ε_0, ε_1, ε_2, and ε_3 obtained from the FWM multiplexing technique proposed in Section II. Table I

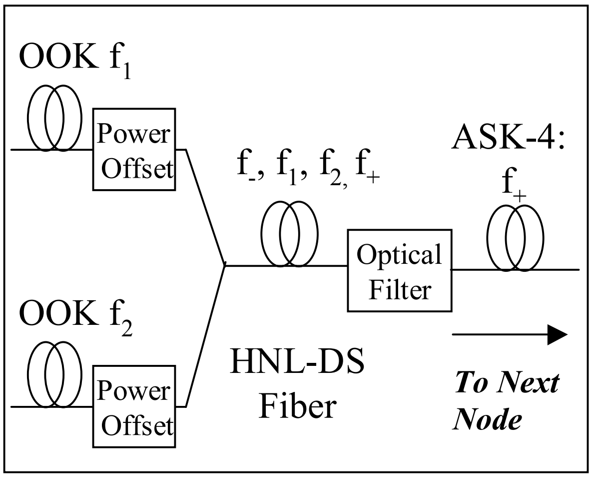

Fig. 3. Proposed Optical Multiplexer. Two traditional OOK signals, at f_1 and f_2, are power offset and multiplexed into a HNL-DS Fiber. FWM generates ASK-4 sidebands at f_- and f_+. f_-, f_1 and f_2 are filtered and f_+ is transmitted to the next optical node. Spectral efficiency is doubled.

summarizes these results for f_- and f_+. It is assumed that ε_0, ε_1, ε_2, and ε_3 are, respectively, originated from the dibits 00, 01, 10, and 11 carried out by the main channels. It is also admitted that power levels are sufficiently weak, so that conversion efficiency, η, may be considered power-independent [15].

Walklin *et al.* [8] investigated optimal level spacing for detecting an electronically generated optical ASK-4 signal, under different dominating noise conditions. If noise is signal independent, optimal detection is achieved for equally-spaced optical levels. This is the case when thermal noise dominates. In case of noise being linearly proportional to optical power, like in ASE (Amplified Spontaneous Emission) and in shot noise, optical levels must be quadratically spaced. These results are summarized in Table II.

Results pointed out in Tables I and II establish the conditions for optical multiplexing through FWM, at least approximately, lead to ASK-4 optimal level spacing. This will be approached in next section. However, it is remarkable to note that, generating ASK-4 signals with

TABLE I. ASK-4 OPTICAL POWER LEVELS GENERATED BY FWM MULTIPLEXING

	f_-	f_+
$\varepsilon_1 / \varepsilon_0$	ξ_2	ξ_1
$\varepsilon_2 / \varepsilon_1$	ξ_2^2 / ξ_1	ξ_2^2 / ξ_1
$\varepsilon_3 / \varepsilon_2$	ξ_2	ξ_1

TABLE II. OPTIMAL POWER LEVEL SPACING UNDER DIFFERENT NOISE DOMINANCE CONDITIONS [6].

	Noise is Signal Independent	Noise is Linearly Proportional to Optical Power
$\varepsilon_0 =$	Arbitrary	0
$\varepsilon_1 =$	$\varepsilon_0 + \xi / 3$	$\varepsilon_3 / 9$
$\varepsilon_2 =$	$\varepsilon_1 + \xi / 3$	$4\varepsilon_3 / 9$
$\varepsilon_3 =$	$\varepsilon_2 + \xi / 3$	Arbitrary

optimal space-levels will not necessarily imply an optimal detection, since transmission may be subjected to fiber nonlinearities.

IV. SIMULATIONS

Simulations presented in this section were performed with LightSim, an optical communications simulator that is being developed by the Photonics Technology Labs group of School of Electrical and Computer Engineering, at UNICAMP. Concerning to fiber transmission, this software utilizes a symmetrized Split-Step Fourier algorithm [14] for solving Generalized Nonlinear Schrödinger Equation. Main results of this section were also checked out with VPI™ simulator, from Virtual Photonics, Inc.

First, we show that the technique proposed in Section II may generate ASK-4 signals obeying, approximately, the optimal level spacing pointed out in [8]. For this, two 10 Gbits/s with offset NRZ codification are co-propagated over a 4 km-long HNL-DS fiber. Fiber parameters are as in [19] ($\alpha = 0.61\, dB/km, \gamma = 13.8\,(W.km)^{-1}$, and $S(\lambda) = S_0 =$ $0.03\, ps/(nm^2 km)$), except by zero dispersion-wavelength that is hypothetically at $\lambda_0 = 1550\, nm$. WDM channels are ITU-T [20] recommended channels, $f_1 = 193.4\, THz$ $(1550.11\, nm)$ and $f_2 = 193.3\, THz$ $(1550.92\, nm)$ and the words carried out by these channels are, respectively, 00101001100 and 00110100100. Measures are taken at $f_- = 193.2\, THz$ $(1551.72\, nm)$.

Figure 4 shows simulation results considering optimal level spacing in the dominance of thermal noise. Average optical power of main channels are $P_1 = 8.6\, dBm$ and $P_2 = 5.6\, dBm$. Analogously, Figure 5 shows the generation of an ASK-4 signal with optimal spacing under ASE noise dominance. In this case, $P_1 = 12.6\, dBm$ and $P_2 = 9\, dBm$.

Figures 4 and 5 corroborate our theoretical proposal for optical multiplexing through FWM. Moreover, they indicate that this multiplexer can generate optimal

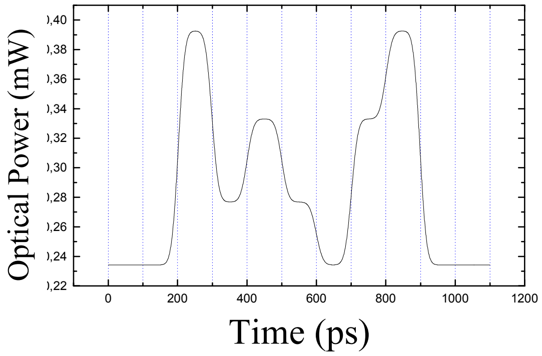

Fig. 4. Optical ASK-4 signal obtained from FWM interaction between two offset 10 Gbit/s NRZ signals. Power levels optimize detection under thermal noise dominance.

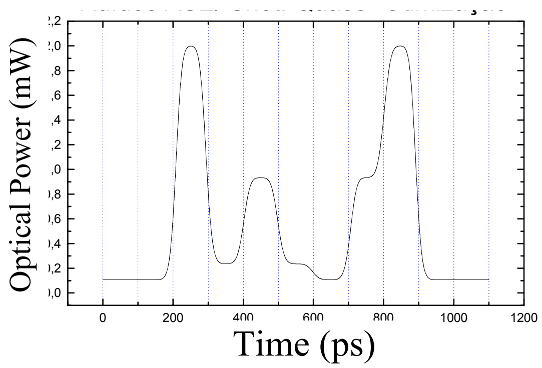

Fig. 5. Optical ASK-4 signal obtained from FWM interaction between two offset 10 Gbit/s NRZ signals. Power levels optimize detection under ASE or shot noise dominance.

detection power level signals, according to those established by [8].

Finally, we need to discuss ASK-4 signal transmission between optical nodes. For this sake, we consider propagation of a 2-channel WDM system ASK-4 signals. Fiber transmission length is 100 km, channels are supposed to be 200 GHz apart (carrier frequencies are $193.4\,THz$ and $193.6\,THz$) and their bit rates are 20 Gbits/s. Input power is the same indicated in Figure 5. At the end of transmission, signals are optically amplified with a 20 dB-small gain Erbium-Doped Fiber Amplifier. Optimal ASK-4 level-spacing for ASE noise is admitted at multiplexer output.

Figures 6-8 show the eye diagram for this propagation over three different kinds of fiber: Standard Fiber (Figure 6), Lucent True Wave™ Fiber (Figure 7), and Dispersion Shifted Fiber (Figure 8). Due to a limitation on our simulator, noise is omitted from our figures.

The low quality eye diagram on Figure 6 suggests that 100 km is a prohibitive propagation distance for ASK-4

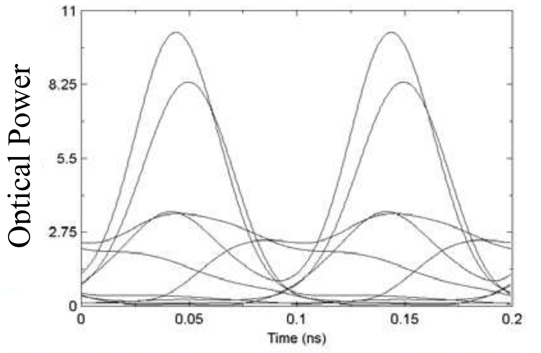

Fig. 6. ASK-4 Eye Diagram after a 100-km Standard Fiber Propagation. Optimal ASK-4 level-spacing for ASE noise is admitted at multiplexer output.

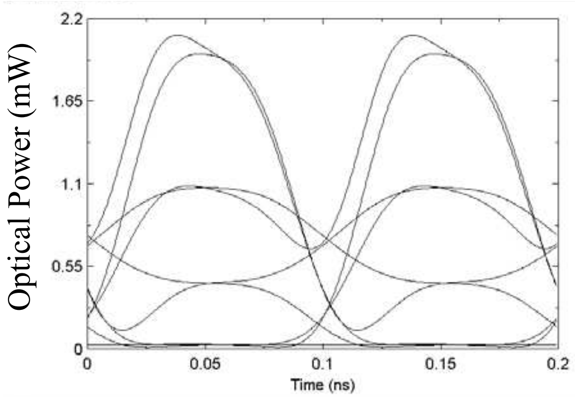

Fig. 7. ASK-4 Eye Diagram after a 100-km Lucent True Wave ™ Fiber Propagation. Optimal ASK-4 level-spacing for ASE noise is admitted at multiplexer output.

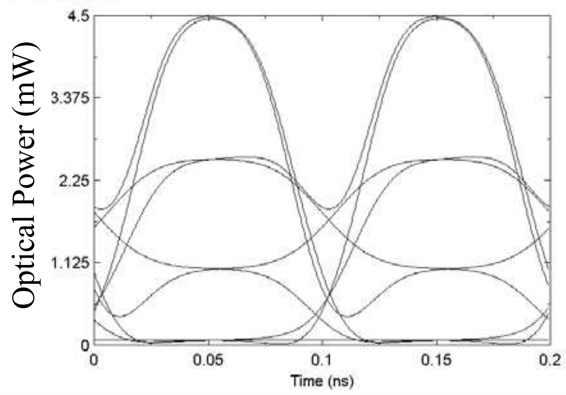

Fig. 8. ASK-4 Eye Diagram after a 100-km Dispersion Shifted Fiber Propagation. Optimal ASK-4 level-spacing for ASE noise is admitted at multiplexer output.

signals over Standard Fibers. In fact, as pulse width is ~ 10 ps this must be true for traditional OOK signals too.

It is observed that low dispersion fiber, like Dispersion Shifted and True Wave ™ fibers (Figures 7-8), allow ASK-4 signal propagation over the tested link length. An interesting point is that the optimal levels at the output of the multiplexer, used in our simulations, do not guarantee an optimal detection after fiber propagation. The reason for this is that fiber nonlinearities may distort signals, changing the relative power levels.

Despite the greater eye-opening presented in Figure 8 for Dispersion Shifted Fibers, we verify that power levels for the True Wave ™ (Figure 7) are closer to the optimal detection pointed out in Table II. This could be expected, since the lower dispersion of Dispersion Shifted fiber tends to enhance fiber nonlinearities [9]. Influence of fiber nonlinearities on ASK-4 signals, as WDM channels spacing decreases is left for a future work.

V. Conclusions

This paper presented a theoretical proposal for optical multiplexing two OOK WDM channels into a single ASK-4 channel. It is based on well-known expressions for estimating the generated power from FWM interaction and is in accordance to recent efforts to improve spectral efficiency. Simulation results satisfactorily corroborated theoretical expectations.

From an application point of view, the proposed technique could be used to increase bandwidth capacity in links experiencing high data traffic. For accomplishing this, it is mandatory to use some technique that assures synchronization between data streams to be multiplexed. As emphasized in Section II, it is also necessary to shift logical zero-level to an appreciable optical power level, before FWM occurs.

Optical ASK-4 signals have already been studied in literature [8], but it is assumed that signal is electronically generated. To authors´ knowledge, this is the first report on ASK-4 signals optical generation.

Nowadays, physical experiments involving the proposed technique are to be performed in the labs of Ultrafast Phenomena and Optical Communications Group of Insitute of Physics, at UNICAMP.

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