REVIEW OF CONFIGURATIONS AND APPLICATIONS OF FIBER OPTICAL PARAMETRIC AMPLIFIERS

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ABSTRACT

A review of the two basic configurations of Fiber optical parametric amplifiers and their typical applications is presented. As these types of amplifiers possess high gain and low noise at arbitrary wavelength, they could be enablers to increase overall capacities in optical communication. The presence of an idler at the output of each signal from an optical parametric amplifier can be utilized for making very wideband wavelength converters. Fiber optical parametric amplifiers can also be used for linear signal amplification, all – optical signal sampling, optical pulse generation, etc.

SIGNIFICANCE: Fiber optical parametric amplifiers offer high gain and wide wavelength. Thus, they can be tailored to operate at any wavelength within the low loss optical communication window centered on 1550 nm.

KEYWORDS: Fiber optical parametric amplifiers (FOPA), Gain, Linear, Amplification, Wavelength, Conversion, Applications.

1.0 INTRODUCTION

Fiber optical parametric amplifiers (FOPA) appear to be a promising technology for signal amplification in the optical domain for future optical communication networks. FOPA possess large and flexible bandwidth (Marhic *et al*., 1996a; Marhic *et al*., 1996b; Ho *et al*., 2001; Hansryd and Andrekson, 2001; Marhic *et al*., 2004) that can be utilized to amplify an optical signal in an arbitrary centered wavelength within the low loss optical communication window. A record optical fiber gain of 70 dB has experimentally been demonstrated in a continuous – wave pumped FOPA (Torounidis *et al*., 2006). A unique feature of FOPA is the unidirectional gain which results in no backward propagating amplified spontaneous emission (ASE) noise. This particular feature is expected to allow for the design of a very high gain amplifiers in contrast to the current widely deployed optical amplifier, the erbium – doped fiber amplifier (EDFA). The amplification bandwidth of the EDFA is limited to the erbium bandwidth of 35 nm. Also, there has been a proposed fundamental limit to the internal gain of the EDFA at 57 – 70 dB due to internal Rayleigh scattering being amplified in the backward direction of the EDFA (Hansen *et al.*, 1992). Apart from linear optical signal amplification, FOPA can be used in a wide range of other applications in the optical communication systems. It allows for ultra fast all – optical signal processing, in – line amplification (Yang *et al.*, 1996; Hansryd *et al.*, 2002), return–to–zero (RZ) pulse generation (Hansryd and Andrekson, 2001), optical wave – division – multiplexing (WDM) (Hedekvist *et al.*, 1997), wavelength conversion (Ho *et al*., 2001; Westlund *et al*., 2002), all optical limiters ((Takada and Imajuku, 1996; Hedekvist *et al*., 1997), and all optical sampling (Li *et al.*, 2001). Presented in this article is a review of the basic configurations and typical applications of the Fiber optical parametric amplifiers.

2.0 FOPA CONFIGURATION

An intense pump and a signal are combined in an optical fiber to form what is commonly known as fiber optical parametric amplifier (FOPA). A FOPA can operate with a continuous wave (CW) pump or pulsed pump. A CW pump is however fully bit rate transparent, requires no synchronization and the pump does not suffer from SPM or induced XPM (Hansryd *et al.,* 2002). The disadvantages of the CW pump are that the CW pump requires higher average pump power and the decreased stimulated Brillouin scattering (SBS) threshold (Agrawal, 2001). Thus for a CW pumped FOPAs, methods to overcome the above mentioned drawbacks are essential. Two methods are proposed to increased the SBS threshold of CW FOPAs, broadening of the pump spectrum by PM (Hansryd *et al.*, 2002) or arrangement such as strain or temperature distribution, to broaden the Brillouin gain bandwidth of the fiber (Shiraki, *et al*., 1996; Hansryd and Andrekson, 2001). Drawback of the method of broadening of the pump spectrum by PM is chirping of the idler spectrum as a consequence of underlying FWM process. FOPA can be pumped by a single pump or two pumps. FOPA pumped by one pump is referred to as degenerated case while those pumped by two pumps are called nondegenerated case (Ho, 2001).

2.1 One–Pump Fiber Optical Parametric Amplifier (1P – FOPA): A degenerate 1P–FOPA is characterized by four–wave mixing process as illustrated in Figure 2.1, where two pump photons (ω_1) are annihilated to create signal (ω_{1-}) and idler (ω_{1+}) photons (Radic and McKinstrie, 2003).

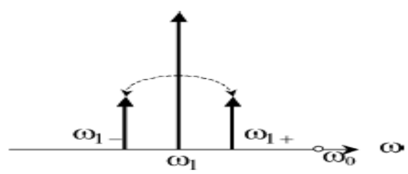

Figure 2.1: FWM in a single–pump parametric amplifier (ω_o indicates the zero – dispersion frequency)

Amplification can be accurately described using FWM process (Stolen and Bjorkholm, 1982; Ho, 2001) which predicts exponential gain within the anomalous dispersion regime. The FOPA gain depends on the optical pump power and dispersion properties of the fiber waveguide. In the degenerate case, light will only be transferred to the signal and idler frequencies (Hansryd and Andrekson, 2001). The signal power gain and the conversion efficiency (Gale *et al*., 1998; Ho, 2001; Hansryd, *et al*., 2002) are given by:

$$G_s = 1 + [\frac{\gamma p_o}{g}\sinh(gl)]^2 \quad \ldots \quad (2.1)$$

$$G_i = G_s - 1 \quad \ldots \quad (2.2)$$

Where p_o is the pump power, γ is nonlinearity coefficient, l is the fiber length and g is the parametric gain given by

$$g^2 = -\Delta\beta[\frac{\Delta\beta}{4} + \gamma p_o] \quad \ldots \quad (2.3)$$

Where $\Delta\beta$ is the propagation constant mismatch ($\Delta\beta = \beta_3 + \beta_4 - 2\beta_1$); β_3, β_4 and β_1 are the propagation constants of signal, idler and pump respectively.

Arrangement for a degenerated case involving one pump at frequency ω_p, one signal at frequency ω_s and one idler at frequency ω_i is shown in Figure 2.2 (Hansryd *et al.,* 2002).

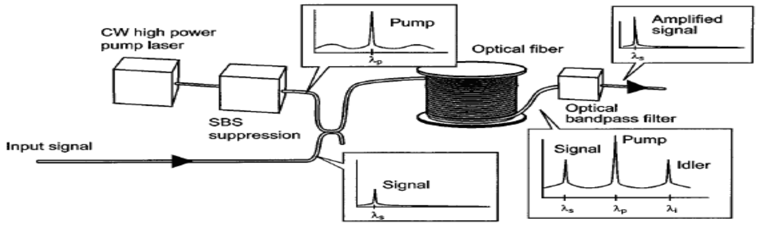

Figure 2.2: A general scheme of a degenerate fiber – based optical parametric amplifier

A requirement for FWM process to resonant is that both the phase – matching condition between the signal waves is maintained and that the frequencies of the three waves are symmetrically positioned relative to each other, i.e.

$\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p) = 0$ … (2.4)

$2\omega_p = \omega_s + \omega_i$ … (2.5)

Where $\Delta\beta$ is the low propagation mismatch, $\beta_{s,i,p} = \omega_{s,i,p} n(\omega_{s,i,p})/c$, c being the speed of light in vacuum.

Despite their many useful features however, one pump FOPAs have several drawbacks among the prominent ones are,

i. The pump frequency overlaps the signal band which makes the pump signal to be difficult to filter (Ho, 2001).
ii. The gain spectrum is not flat over the amplifier bandwidth, which makes it difficult to equalize the power of the various channels in wavelength – division – multiplex (WDM) systems (Ho, *et al*., 2001).
iii. When operated in continuous wave (CW) mode, the idler spectrum is broadened due to the required pump dithering which degrades the bit error rate (BER) when FOPAs are used as wavelength converters (Wong *et al*., 2002)

2.2 Two–Pump Fiber Optical Parametric Amplifier (2P–FOPA): To overcome the above mentioned problems associated with 1P-FOPAs, the concept of 2P–FOPAs was developed. The 2P–FOPAs provide broader bandwidth and flatter gain spectrum by suitable use of dispersion control (Boggio *et al*., 2003). When the two pumps are tuned nearly symmetrical to the zero dispersion frequency of the fiber, phase matching is obtained over a broad spectral bandwidth and the gain spectrum is nearly flat (Agrawal, 2002). It has the potential of providing polarization – independent performance by use of orthogonal pumps. It also has the ability to cancel pump dithering induced by idler broadening. The underlying process in the two pump FOPAs is the parametric interaction between two pumps (frequencies at ω_1 and ω_2), the signal at frequency ω_s and an idler at frequency $\omega_i = \omega_1 + \omega_2 - \omega_s$. as illustrated in Figure 2.3 (Radic and McKinstrie, 2003).

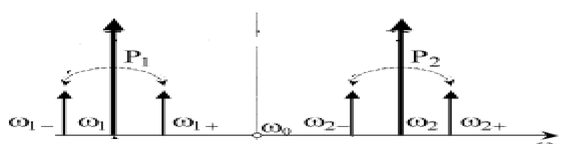

Figure 2.3: Two–pump FWM process ($P_{1,2}$ are pumps $1\pm, 2\pm$ are the parametric sidebands)

A unique feature of the 2P–FOPA is the existence of four amplification (or conversion) bands, which offer a number of configurations for narrow idler generation (McKinstrie *et al*., 2002) as illustrated in Figure 2.4.

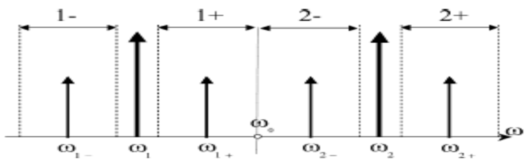

Figure 2.4: Spectral bands in 2P–FOPA (Inner band (1+ and 2-), Outer band (1- and 2+), $\omega_{1\pm}, \omega_{2\pm}$ are any combination of signal and generated idlers; $\omega_{1,2}$ are pump frequencies; ω_o is the zero – dispersion frequency)

In the first configuration, we consider a signal positioned within the inner (1+) band $(\omega_s = \omega_{1+})$. Following the notation outlined in Fig. 2.4, idler generation can, to first order, be described by a set of FWM processes:

$$\omega_{2-} = (\omega_1 + \Delta\omega_1) + (\omega_2 + \Delta\omega_2) - \omega_s, \ \ldots \quad (2.6)$$

$$\omega_{1-} = 2(\omega_1 + \Delta\omega_1) - \omega_s, \quad \ldots \quad (2.7)$$

$$\omega_{2+} = (\omega_2 + \Delta\omega_2) + \omega_s - (\omega_1 + \Delta\omega_1), \ldots \quad (2.8)$$

Where $\Delta\omega_{1,2}$ represents the instantaneous deviations from the pump center frequencies induced by phase modulation.

In the case of pump counter – phasing $(\Delta\omega_1 = -\Delta\omega_2)$, the ω_{2-} idler spectrum will not be broadened, and will, therefore, replicate the shape of the original signal (ω_s) spectrum. Equation (2.7) states that the idler generated at ω_{1-} will be broadened regardless of the relative pump phasing scheme. Similarly, Equation (2.8) implies that broadening at ω_{2+} in the case of pump counter phasing. Pump co – phasing $(\Delta\omega_1 = \Delta\omega_2)$ will result in narrow ω_{2+} generation, while simultaneously broadening the idler ω_{2-}. In other words, by choosing the pump-phasing technique, one can alternate broadening suppression between the ω_{2-} and ω_{2+} idlers. Similar results apply if $\omega_s = \omega_{2-}$. The ω_{1-} and ω_{1+} broadenings can be suppressed conditionally, whereas ω_{2+} is always broadened. An equally interesting picture emerges if one chooses to place the signal within one of the outer bands (1− or 2+). Placing the signal at $\omega_s = \omega_{2+}$ will result in idler generation described by following set of processes:

$$\omega_{2-} = 2(\omega_2 + \Delta\omega_2) - \omega_s, \quad \ldots \quad (2.9)$$

$$\omega_{1+} = (\omega_1 + \Delta\omega_1) + \omega_s - (\omega_2 + \Delta\omega_2), \ldots \quad (2.10)$$

$$\omega_{1-} = (\omega_1 + \Delta\omega_1) + (\omega_2 + \Delta\omega_2) - \omega_s \ldots. \quad (2.11)$$

Pump counter – phasing $(\Delta\omega_1 = -\Delta\omega_2)$ now narrows the spectrum of the ω_{1-} idler, while broadening the ω_{1+} spectrum. Pump co – phasing $(\Delta\omega_1 = \Delta\omega_2)$ reverses this outcome, broadening ω_{1-} and narrowing ω_{1+}. The degenerate process responsible for ω_{2-} generation will always result in a broadened spectrum. When the two pumps are tuned nearly symmetrical to the zero dispersion frequency of the fiber, phase matching is obtained over a broad spectral bandwidth and the gain spectrum is nearly flat (Agrawal, 2002). The configuration of a two pump OPA is given in Figure 2.5 (Ho, 2001).
Under the assumption that there is no pump depletion (the pump power is more stronger than the signal power, so that the pump power can be assumed to be constant throughout the fiber) and single polarization (i.e. all the waves have the same linear state of polarization), the signal and idler gain for a 2P – FOPA, over a fiber length *L* can be expressed (Ho, 2001) as:

$$G_s = 1 + [\frac{ur}{g}\sinh(gL)]^2 \quad \ldots \quad (2.12)$$

$$G_i = G_s - 1 \quad \ldots \quad (2.13)$$

The parametric gain, g in (2.12) is given by

$$g^2 = -\frac{1}{4}(\Delta\beta^2 + 2u\Delta\beta + u^2 - 4u^2r^2) \ \ldots \ 2.14)$$

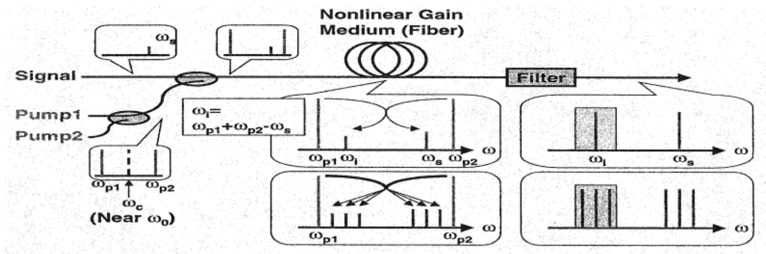

Figure 2.5: Configuration of a two–pump FOPA

The parameters *u* and *r* are defined as

$$u = \gamma(P_1 + P_2) = \gamma P_o \ \ldots \qquad (2.15)$$

$$r = \frac{2}{\sqrt{P_1/P_2} + \sqrt{P_2/P_1}} = \frac{2\sqrt{P_1P_2}}{P_o} \quad \ldots \ (2.16)$$

Where: $P_o = P_1 + P_2$, $P_{1,2}$ being the pump powers; $\Delta\beta$ is the linear propagation–constant mismatch, determined by the waveguide characteristics. $\Delta\beta = \beta_3 + \beta_4 - \beta_1 - \beta_2$, where $\beta_3, \beta_4, \beta_1$ and β_2 are respectively propagating constant of the signal, the idler and the two pumps.

3.0 FOPA APPLICATIONS

3.1 Linear Optical Amplifier: The application of optical amplifiers in linear amplification can be categorized into three groups - booster amplifiers, inline amplifiers and preamplifiers. In the **booster amplifier** class, the amplifier is placed immediately after the transmitter, before the signal enters the transmission fiber. They compensate for losses in the transmitter due to connectors, modulators or multiplexers in WDM systems. An amplifier in this category can increase the transmission distance by 100 km or more depending on amplifier gain and the fiber losses (Agrawal, 2001). **In–line optical amplifiers** on the other hand, replace optical regenerators and compensate for fiber losses during transmission, which also increases the transmission distance of the optical signal. They are more attractive in the WDM systems where all channels are amplified simultaneously. **Pre–amplifiers** are placed just before the signal enters the receiver to boost the received power. In this way, they increase receiver sensitivity.

Hansryd and Andrekson (2001) experimentally demonstrated a Continues Wave pumped FOPA providing a 49 dB gain and a 39 dB net “Black–Box gain” (signal at fiber output divided by signal at fiber input minus output and input power losses). Prior to this experiment, no demonstration exists reporting an FOPA providing a net black – box gain. FOPA have essentially been considered not to have sufficient performance to be of interest as amplifiers in fiber optic communication systems. The result of the experiment shows that FOPA may indeed be considered a real candidate in the future and may compete favorably with doped fiber amplifiers and fiber Raman amplifiers. Figure 3.1 shows the experimental set – up.

In the experiment, a CW distributed feedback (DFB) laser diode with a wavelength 2 nm above λ_o of the fiber was used as pump source. The pump is PM to broaden its spectrum using four combined sinusoidal RF frequencies, increasing the SBS threshold from 17 to > 33dBm. It is then amplified to approximately 2W and combined with the signal using a 90/10 coupler, adding 90% of the pump with 10% of the signal. The combined pump and signal are coupled to a 500m HNLF that consisted of three pieces of 200m, 200m and 100m fiber with zero dispersion wavelength λ_o equal to 1556.8nm, 1560.3nm and 1561.2nm respectively. An optical bandpass filter (BPF) was placed after the fiber to recover either the generated idler or the signal.

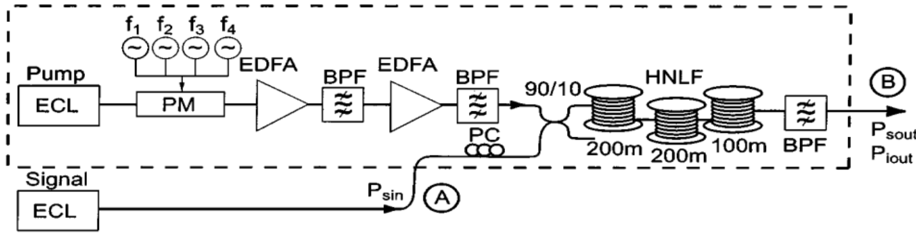

Figure 3.1: Experimental setup demonstrating 39-dB CW pumped net "black-box" parametric gain. (EDFA - Erbium-doped fiber amplifier, ECL - External cavity laser, PM - Phase modulator, BPF - Optical band pass filter, OSA - Optical spectrum analyzer, PC - Polarization controller, HNLF - Highly nonlinear fiber).

The amplifier provided net gain over > 35nm with a peak net gain of 39 dB. Bit – error – rate (BER) measured, also shows sensitiveness comparable to typical EDFA when compensating for signal in – coupling loss. By filtering out the generated idler, wavelength conversion with inherent gain is obtained. Another application of the same scheme is optical phase conjugation (Wong *et al.*, 2003), in which case the quality of the optical spectrum for the generated idler is essential. In another experiment by another research group in the same year, (Ho *et al.*, 2001) demonstrated FOPA with a 200 – nm bandwidth. Wong, *et al.* (2003) reported increased of gain of FOPA than reported by Hansryd and Andrekson (2001). They were able to obtain a CW FOPA with 60 dB internal gain (ON – OFF) by using an in – line isolator between two high nonlinear fibers (HNLF) in order to increase the pump SBS threshold so as to suppress SBS. The highest fiber gain in FOPA so far was reported by Torounidis *et al.*, (2006). A peak gain of 70 – dB was obtained. The gain was achieved using an efficient SBS suppression on both the pump and the amplified signal. Figure 3.4 shows the experimental set. An ON – OFF gain of 71 dB was obtained which does not account for the losses in the fiber. The output was however limited due to both saturation effects from ASE and by SBS on the amplified signal. Demonstration of high gains in FOPA is important for several reasons among which are; shows that gain saturation can be reached for low – signal input power, which can be used for amplitude noise reductions (Inoue and Mukai, 2002) and that it could be used for ASE sources, preamplifiers in a low bit rate communication systems (Torounidis *et al*., 2006).

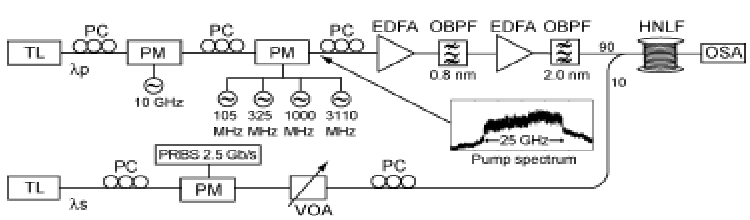

Fig. 3.4 Experimental set – up (Wong *et al.*, 2003)

3.2 Wavelength Converter: A wavelength converter changes the input wavelength to a new wavelength without modifying the data content of the signal. All – optical wavelength conversion is a key technology for improving the flexibility and increasing the capacity of optical fiber networks (Yoo and Bellcore, 1996). Many schemes for making wavelength converters were developed (Yoo and Bellcore 1996; Yasaka *et al.*, 1997; Uchida *et al.*, 1998); Yu, *et al.*, 2000; Uesaka, *et al.*, 2002). Among the various schemes, the use of parametric four–wave mixing (FWM) attracted considerable attention. (Tang, *et al.*, 2005) experimentally demonstrated a parametric wavelength conversion with efficiency larger than 0 dB over 50nm (Figure 3.6). The results of the experiment show that highly efficient wavelength conversion is realized between Stokes and anti-Stokes light around the pump wavelength.

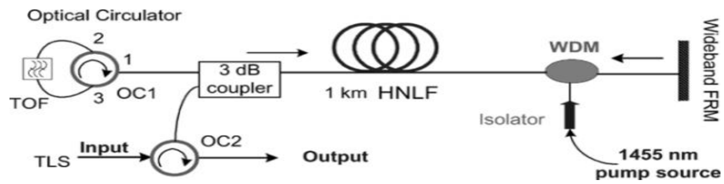

Figure 3.6: Experimental – setup demonstrating wavelength conversion.

3.3 Return-to-zero (RZ) Pulse Generation: Figure 3.8 shows the experimental set up for generating 40 GHz RZ pulses from a single frequency sinusoidally amplitude – modulated pump (Hansryd, *et al.*, 2002).

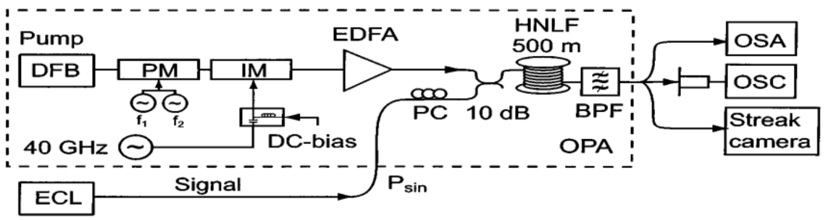

Figure 3.8: Experimental setup for 40-GHz RZ pulse source (ECL - External cavity laser, DFB - Distributed feedback laser diode, EDFA - Erbium-doped fiber amplifier, PM - phase modulator, IM - Mach–Zehnder intensity modulator, BPF - Optical bandpass filter, OSA - Optical spectrum analyzer, OSC - Digital oscilloscope, PC - Polarization controller, HNLF - Highly nonlinear fiber).

The principle of operation is to selectively amplify a weak CW signal and either recover the signal or the generated idler as the pulse source (Clausen, *et al.*, 2001; Hansryd and Andrekson, 2001). High power and very stable 40 – GHz pulses at both signal and idler wavelength with width between 2 and 4 ps over a 37 nm wide wavelength range were obtained (Figure 3.9).

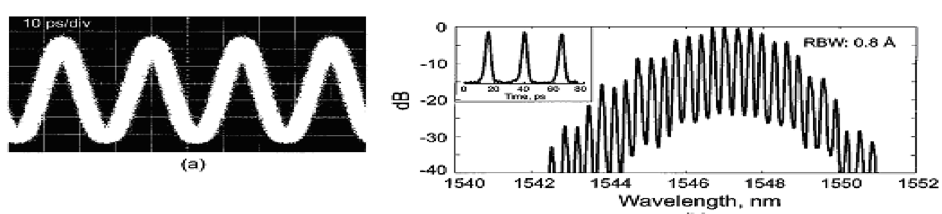

Figure 3.9: (a) Received 40 GHz pulses; (b) Optical spectrum for the pulses at the signal wavelength. The inset shows a streak camera trace of a generated 40-GHz pulse.

3.4 Optical–Time Division Multiplexing (O-TDM) Switch: The narrow gain time window profile in pump modulated FOPAs may be utilized in ultrahigh – speed O–TDM switches. Hansryd and Andrekson (2001) used a 10 GHz sinusoidally modulated pump to demultiplex a 40 Gb/s O–TDM signal. The principle used is to selectively amplify a predetermined O–TDM channel (Figure 3.10).

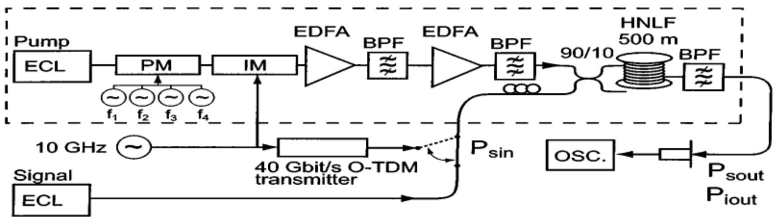

Figure 3.10: Experimental setup for a 40 to 10 Gb/s OPA-based time demultiplexer. ECL - External cavity laser, EDFA - Erbium-doped fiber amplifier, PM - Phase modulator, IM - Mach–Zehnder intensity modulator, BPF - Optical bandpass filter, OSA - Optical spectrum analyzer, OSC - Digital oscilloscope, PC - Polarization controller, HNLF - Highly nonlinear fiber.

In order to be able to switch between a 40 – Gb/s O – TDM signal and a CW signal generated by a wavelength tunable ECL, a switch is inserted in front of the input signal port. The CW signal was used for measuring the resulting FWHM of the switching window by detecting the partially amplified/wavelength converted signal on an oscilloscope.

3.5 All–Optical Sampling: All–optical sampling is a technique used to evaluate a received high bit rate signal. This will enable a direct monitoring of optical signals over communication systems. Parametric amplification based all – optical sampling is a similar application to the O – TDM switch. Before the development of HNLF, optical fibers were not considered for such application because of the small nonlinear coefficient (Takara *et al.*, 1996; Ohta *et al.*, 2000). Li *et al.*, (2001) described all – optical sampling application using fiber based parametric amplification. The experimental set up is shown in Figure 3.11.

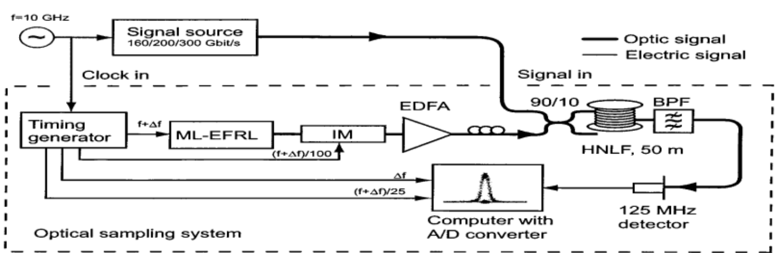

Figure 3.11: Experimental setup for an optical sampling system based on parametric amplification. ML-EFRL – 10 GHz actively mode-locked Erbium fiber ring laser; EDFA - Erbium-doped fiber amplifier; IM - Mach–Zehnder intensity modulator; BPF - Optical bandpass filter; OSA - Optical spectrum analyzer; HNLF - Highly nonlinear fiber.

The data signal studied was a busted O–TDM signal at 160 Gb/s, 200 Gb/s or 300 Gb/s. The sampling system uses a mode–locked Erbium–doped fiber ring laser (ML–EFRL) generating 1.6 ps – wide pulses at the original 10 Gb/s O–TDM channel repetition frequency plus a slight deviation Δf. An intensity modulator removes most pulses so that 1.6 ps FWHM sampling pulse at about 100 MHz repetition rate are generated and subsequently combined with the studied data signal. Figure 3.12 shows sampled 160, 200 and 300 Gb/s eyes. Parametric gain is achieved over more than 30nm with at least 20 dB signal–to–noise ratio for a minimum input signal peak power of 10mW.

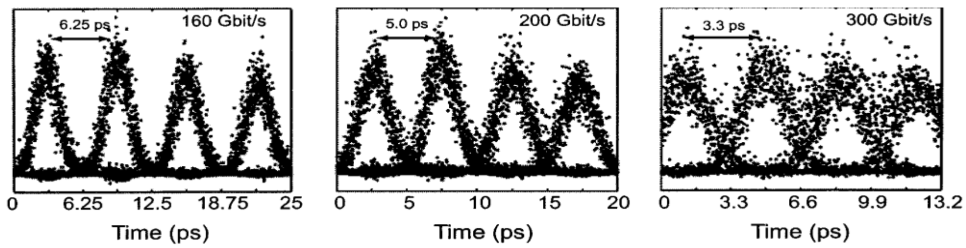

Figure 3.12: Sampled eye diagrams of 160, 200, and 300 Gb/s optical signals

4.0 CONCLUTIONS

Although they have not been practically used the prospects of FOPA in practical applications are very promising. Their main advantages are the built-in multifunctionalities and their ability to operate over arbitrary centered and wide wavelength. While some of their applications are presented, some more applications are likely to be proposed and demonstrated in future, especially with the development of highly non-linear fibers like the photonic crystal fibers and the availability of high power pumps. In particular, the future trends in optical parametric amplification will lead to: -

1. Possibility of ultra–high speed optical communications;
2. Extending the limit of broadband, long–span operations;
3. Expansion of area coverage in communication networks;
4. Evolution of new functions enabled by greater bandwidth, such as i) All optical signal processing, ii) Personal video conferencing, imaging and pictures, iii) E–Business that will require increasingly voluminous instant transfer of numeric and graphical data, and iv) Remote education (Distance learning) and many others to be proposed later;
5. Improved proliferation of internet services;
6. Higher data transfer rate in global communications.

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