Factors affecting dual pump fiber optical parametric amplification gain

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***Abstract*-**The fiber nonlinear effects on the gain of fiber optical parametric amplifier (FOPA) are theoretically studied using MATLAB and optism. The results show that different channels interact giving varied degrees of polarization (DOP) at different channel spacing. It is also found out that the parametric gain increase with the increase in nonlinear parameter and fiber length. This study is of great significance in improving the transmission capacity of a long haul system and dense wavelength division multiplexing.

***Keywords*-** DOP, FOPA, Four-wave mixing, nonlinear dispersion, optical fiber, Transmission.

Introduction

Fiber optical parametric amplifier (FOPA) is versatile and can be used as an optical amplifier and variety of all-optical signal processing for future ultra fast optical networks such as wavelength conversion, optical multiplexing, sampling, limiting, switching, noise and dispersion monitoring [1]. FOPAs exhibit low noise figures [3] [4] that can be equivalent to those of conventional optical fiber amplifiers, or even better when they operate in a phase sensitive configuration. The uniformity of the gain band is however an important issue of optical amplifiers of current interest, especially in dense wavelength multiplexing systems (DWDM). Owing to the phase matching conditions for the underlying Four-Wave Mixing (FWM) process, single pump FOPAs generally exhibit poor gain flatness in the zero

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dispersion wavelength (ZDW) region of the optical fiber [5]. In response to this limitation, the concept of dual wavelength pumping has been developed [2]. Future high capacity systems would require broadband optical amplifiers with low ripple gain spectrum performing also optical networks functionalities as wavelength conversion and optical shaping. A two pump fiber optical parametric amplifiers (2P-FOPA) constructed with a highly nonlinear fiber (HNLF) can fulfill the requirements of multifunctionality and flat spectral response over broadband bandwidth [2]. In this paper, we focus on the theoretical analysis of the parametric gain in 2P-FOPA. This work will go a long way to improve the transmission of information in fibers and be of a great benefit to ICT sector hence alleviating poverty in the country.

Theory

In order to increase the transmission capacity of a DWDM optical system, one can either increase the transmission data rate per wavelength or increase the number of wavelengths. Wavelength Division Multiplexing (WDM) is a technique of sending signals of several different wavelengths of light into the fiber simultaneously. In fiber optic communications, WDM is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths (colors) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to making it possible to perform bidirectional communications over one strand of fiber. Transmitting several wavelengths results in an increase in total optical power, this causes nonlinear interactions to be very effective. The transmission performance of the system can then be seriously degenerated, mainly via nonlinear signal distortion and power transfer between different wavelength channels.

FWM in FOPAs makes use of the cubic non linearity in glass. It requires a strong pump(s) of frequency ω_p and power P_p. The FWM process then generates two photons of frequencies; signal frequency, ω_s and center frequency, ω_c that are symmetrical around pump frequency, ω_p , from the annihilation of two photons at ω_p. Thus

$$2\omega_p = \omega_s + \omega_c \text{ .... (1)}$$

That is, energy is conserved. This process requires phase matching, and its efficiency depends on the wave number mismatch, Δβ, defined by

$$\Delta\beta = 2\beta_p - \beta_s - \beta_c \text{ .... (2)}$$

Two pumps at frequencies ω_1 and ω_2 provide gain to a signal at ω_s with a phase that is determined by the phase mismatch

$$\kappa = \beta_2(\omega_c)\left[\Delta\omega_s^2 - \Delta\omega_p^2\right] + \frac{1}{12}\beta_4(\omega_c)\left[\Delta\omega_s^4 - \Delta\omega_p^4\right] + \gamma(P_1 + P_2) \quad \text{.... (3)}$$

where,

$$\omega_c = \frac{1}{2}(\omega_1 + \omega_2),$$
$$\Delta\omega_s = \omega_s - \omega_c,$$
$$\Delta\omega_p = \omega_1 - \omega_c,$$

β_2 and β_4 are second and fourth order dispersion coefficients respectively.

The parametric gain can be obtained by taking into account the signal and idler waves. This is given by

$$g = \sqrt{4\gamma^2 P_1 P_2 - \left(\frac{k + \delta k}{2}\right)^2} \text{ .... (4)}$$

where k is the standard phase mismatch (given by eq. (3) above) and δk is the instantaneous phase mismatch due to pump phase modulation.

$$\delta k = \frac{\beta_3}{2}\left(\Delta\omega_s^2 - \Delta\omega_p^2\right)\left(\varphi_{1,\tau} + \varphi_{2,\tau}\right) \text{... (5)}$$

where $\varphi_{i,\tau}$ is the first order time derivative of the phase.

Eqs. (4) and (5) together show that the parametric gain depends both on fiber dispersion slope and on the frequency by the pump phase modulation. Note that the instantaneous phase mismatch has negligible dependency on β_2 and β_4. k is a function of Δ ω_s, being a fourth order polynomial, give rise to gain spectra having 7,5,3 or 1 extrema depending on the values of β_2 and β_4 [6] [7].

The net signal gain, G is given by

$$G = 1 + \left(\frac{2\gamma\sqrt{P_1 P_2}}{g}\sinh(gL)\right)^2 \text{ ... (6)}$$

where, g is the parametric gain and L is the fiber length. In FOPA parametric gain is exponential with P_0 and z when phase matching condition is fulfilled, i.e., k=0.The phase matching is mainly determined by the nonlinear phase shift γP_0, whereas the spectral gain profile in the ZDW region is determined by the even-dispersion orders of fibers, β_2 and β_4. The third order dispersion plays no role in the phase matching condition for symmetry reasons. The magnitude and shape of the gain can thereby be optimized by tuning the length and dispersion in the fiber segment [2] [8].

Methodology

The set up was as follows

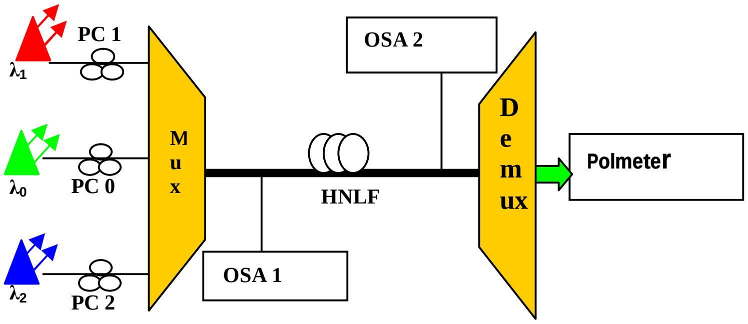

Figure 1: set up. Polmeter: Polarimeter

The setup was as shown in Fig. 1. Three laser sources were used as the pumps (λ_1 and λ_3) and a probe (λ_2). λ_2 wavelength was set at 1550.0 nm while pumps λ_1 and λ_3 were varied depending on channel spacing that gave the best gain. The pumps were multiplexed using a 2x1 multiplexer and launched into a 50-km-long highly nonlinear fiber (HNLF). The signal is to be provided by a continuous wave tunable laser. Its state of polarization (SOP) was adjusted by a polarization controller, PC1. PC3 is to maximize the pump power into the fiber. The spectra of the three sources coupled together were taken by OSA 1 before propagating and by OSA 2 after propagating through the fiber.

On the receiving side, the probe channel was isolated from the pump channels using the demultiplexer. The DOP was measured using a polarimeter as a function of input polarization change. The length of the fiber used was 400m and 600m. Nonlinear coefficient was varied and the gain obtained taken.

Results and discussion

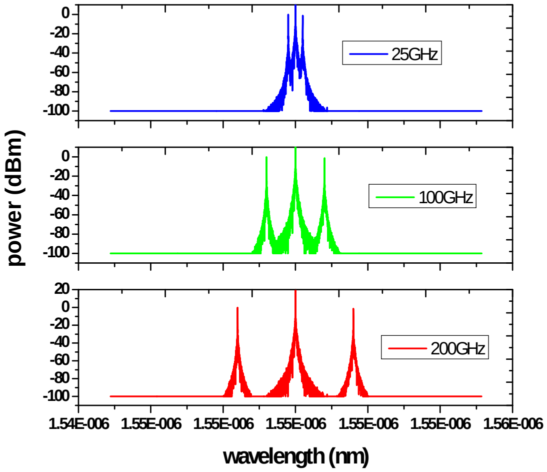

Figure 2. Signal spectrum before passing the optical fiber (SMF or HNLF) at different channel spacing (OSA 1)

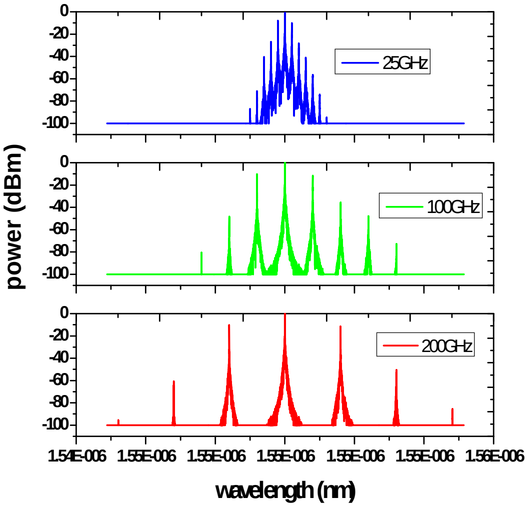

Figure 3: Signal spectrum after passing the optical fiber (SMF or HNLF) for respective channel spacing (OSA 2)

Figure 3 above gives the FWM products generated due to interaction of the three sources. There was an increase in number of new signals with increase in third order dispersion parameter and decrease in channel spacing (due to high interaction). The polarimeter gave a varied pattern on the DOP.

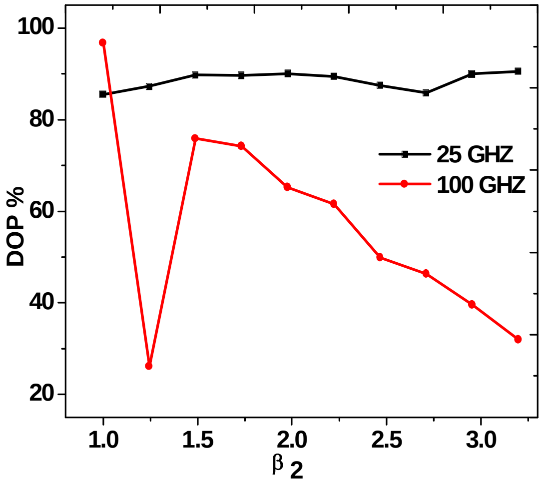

Fig 4(a).

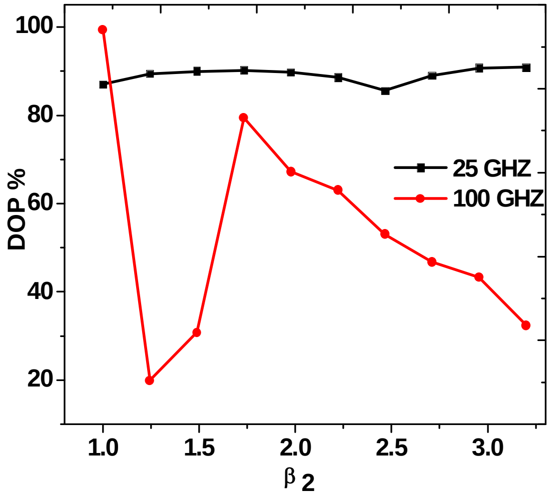

Fig. 4(b)

Figure 4: (a) Graph of DOP (%) against β_2 (ps^2km) at constant β_3 =1.6 (ps^3/km) (b) Graph of DOP against β_2 (ps^2/km) at constant β_3 =1.8 (ps^3/km)

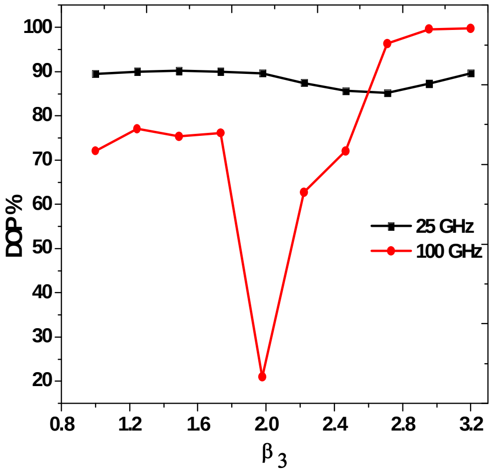

Fig.5 (a)

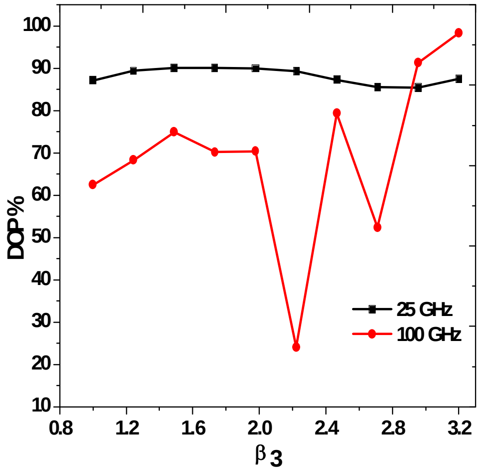

Fig.5 (b)

Figure 5: (a) Graph of DOP (%) against β_3 (ps^3/km) at constant $\beta_2 = 1.6$ (ps^2/km) (b) Graph of DOP (%) against β_3 (ps^3/km) at constant $\beta_2 = 1.8$ (ps^2/km).

Figure 4(a) and 4(b) show the variation of DOP with β_2 at constant β_3. In both cases, channel spacing of 25GHz showed stability in DOP compared to 100GHz.

Figure 5(a) and 5(b) show the variation of DOP with β_3 at constant β_2. Similarly, 25GHz channel spacing gave a stable DOP above 80%. At low values of β_2 and β_3 we have high DOP because signal's optical phase has not been modified. At particular points of β_2 and β_3, we have low values of DOP because the polarization direction has changed and does not coincide with the two axes. As the polarization directions align with the axes there is improvement on DOP and vice versa.

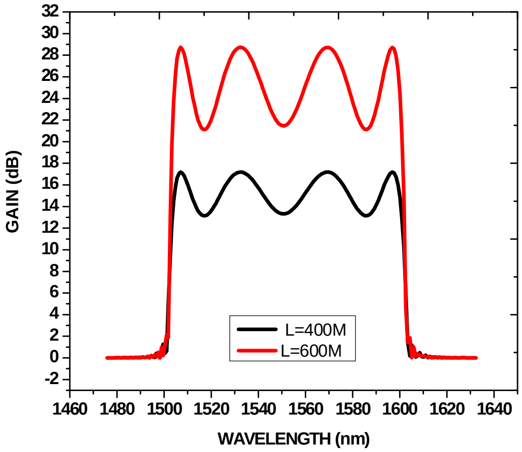

Figure 6(a): graph of gain against wavelength, nonlinear coefficient, $\gamma = 10$ sW^{-1}

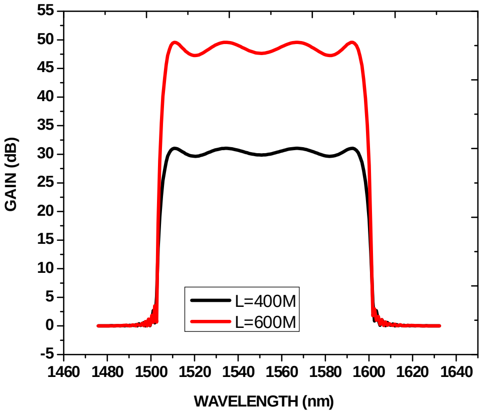

Figure 6(b): graph of gain against wavelength, nonlinear coefficient, γ = 16 sW^{-1}

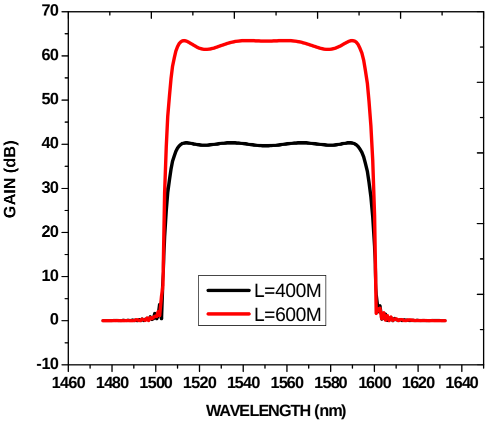

Figure 6(c): graph of gain against wavelength, nonlinear coefficient, γ = 20 sW^{-1} Figure 6(a), 6(b) and 6(c) give gain curves at γ = 10 sW^{-1}, γ = 16 $sW^{-1}$and γ = 20 sW^{-1} respectively. There was an improvement in gain as the nonlinear coefficient was increased from 10 to 20 sW^{-1}over a bandwidth >100nm.At low values of nonlinear coefficient i.e. γ = 10 sW^{-1}, the gain was degraded (not flat) because of polarization mode dispersion, gain dependence on signal SOP and nonlinear effects (even –dispersion order, β_2 and β_4) [5] [9]. As the fiber length was increased from 400m to 600m, the gain improved significantly. The profile on figure 6(a), 6(b) and 6(c) show that an increase in fiber length, L and nonlinear coefficient, γ increase the FOPA gain (agrees with eq. (6) above).

5. Conclusion

In this work, we have shown the factors that affect the gain in FOPAs. In general, both β_2 and β_3 contribute to the fiber dispersion slope which in turn leads to nonlinear polarization rotation and FWM hence affecting the parametric gain. Channel spacing on the other hand, determines the extend of creation of new signals (FWM) arising from interaction between nonlinearities and varying birefringence of the various signals in the fiber. It was also found out that the gain of a FOPA is dependent on fiber length, L and nonlinear coefficient, γ.

Therefore, the magnitude and shape of the gain can be optimized by tuning the fiber length, power and dispersion values. These results should help in improving the transmission capacity in WDM and parametric amplification in long haul systems in fiber optic communication.

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