WAVELENGTH CONVERSION BASED ON XPM IN A SINGLE MODE FIBER AND A MACH-ZEHNDER INTERFEROMETER

B. C. Sarker*, S. P. Majumder, and T. Yoshino*,**

* Department of Electronic Engineering, Gunma University, 1-5-1 Tenjin Cho, Kiryu
Gunma 376-8515, Japan
E-mail : sarker@el.gunma-u.ac.jp

** Faculty of Engineering, Multimedia University, Cyberjaya 63100, Malaysia
E-mail : S.P.Majumder@mmu.edu.my

Abstract :

A wavelength converter based on cross-phase modulation in a single mode fiber followed by a Mach-Zehnder interferometer is analyzed using conventional fiber as well as dispersion shifted fiber (DSF). The results show that all-optical wavelength conversion is possible without significant reduction in conversion efficiency over a wavelength separation of approximately 10 nm between the input pump signal and the probe signal. For 10 Gb/s intensity modulated signal, output converted power is found to be –6.5 dBm for 10 dBm input for pump and probe and conversion is possible over 10 nm of wavelength separation.

1. Introduction

All-optical wavelength converters are the key components for multi-wavelength optical transport networks and offers the advantages of increased flexibility in wavelength routing and avoidance of wavelength blocking in a WDM network node. As a consequence, the capacity of an optical multi-wavelength network is increased with the use of wavelength converters at different nodes. It can be achieved by utilizing the non-linear characteristics viz. cross-phase modulation (XPM), cross-gain modulation (XGM), and four-wave mixing (FWM) [1-2] in optical amplifiers and FWM in fibers. Recent research works on fiber based converters have also been reported utilizing FWM in single mode fibers around zero dispersion wavelength region [3]. The wavelength converters based on FWM in SOA or SMF are superior to others because of transparency to modulation format [4]. On the other hand. XPM converters can be used only for intensity modulated signals. However, on the basis of conversion efficiency, XPM based converters provide better performance compared to the converters based on FWM. In this paper, we propose an wavelength converter based on XPM in a single mode fiber (SMF) with one pump laser and a Mach-Zehnder interferometer (MZI). Analysis is carried out to find the efficiency of wavelength conversion and effect of wavelength separation on the converter signal.

2. Converter model

A schematic model of the proposed wavelength converter is shown in Fig.1. The amplified input intensity modulated signal along with a continuous wave probe signal from the converter laser are given input to a single mode fiber. The intensity modulation of the pump signal modulates the phase of the probe signal by XPM. The MZI is used to convert the phase modulated signal to an intensity modulated signal which is then filtered by a FP filter .

3. Theoretical analysis

We consider the probe to be a continuous wave converter signal at an angular frequency ω_c and the pump signal is an intensity modulated signal at an angular frequency ω_s with average pump power P_s If *m(t)* represents the modulating signal which consists of random NRZ data and *G* is the gain of the optical amplifier then the phase modulation (PM) of the probe signal due to intensity fluctuation of the pump as well as the probe itself in a fiber length of L, can be expressed as [5]

$$f_c(t) = g_c\left[\frac{1-\exp(-aL)}{a}\right]\left|E_c(t-\frac{L}{v_{gc}})\right|^2 + 2g_c\int_0^L \left|E_s(t-\frac{L}{v_{gc}}+d_{cs}z')\right|^2 \exp(-az')dz' \quad (1)$$

where $\gamma_c = \dfrac{2\pi n_2}{\lambda_c A_{eff}}$ is the nonlinear coupling coefficient of the SMF at the wavelength of the probe, n_2 is the nonlinear refractive index of fiber, l_c is the wavelength of the probe signal (converter signal), α is the fiber attenuation coefficient, A_{eff} is the effective core area, v_{gc} is the group velocity at wavelength l_c and d_{cs} is the walk-off parameter for the converter signal and pump signal, and is defined as

$$\begin{aligned} d_{cs} &= (v_{gc})^{-1} - (v_{gs})^{-1} \\ &= \int_{l_s}^{l_c} D_c(l)\,dl \end{aligned} \quad (2)$$

where v_{gi} is the group velocity at a wavelength l_i, and $D_c(l)$ is the dispersion coefficient of SMF at a wavelength λ.

The first term in (1) represents the amount of phase shift in the probe or converter signal due to self-phase modulation (SPM) and the second term shows the amount of phase modulation induced by cross-phase modulation (XPM) caused by the instantaneous intensity of the pump signal.

If $M(w_m)$ represents the spectrum of the modulating signal and since $m(t)$ is a real function, the phase modulation of the converted signal induced by XPM, can be expressed as [5]

$$f_{XPM}(t) = \frac{4g_c GP_s}{p^2}\int_0^L \begin{bmatrix} \int_0^\infty |M(w_m)|\cos[w_m(t-t_0) \\ +\angle M(w_m)]dw_m \end{bmatrix}^2 \times \exp(-az')dz' \quad (3)$$

where $t_0 = (L/v_{gc} - d_{cs}z')$, γ_c is the nonlinear coupling coefficient of the SMF at the wavelength of the probe signal, α is the fiber attenuation coefficient, v_{gc} is the group velocity at wavelength l_c and d_{cs} is the walk-off parameter for the converter signal and pump signal, At the output of the SMF, the converter signal with XPM induced phase modulation can be expressed as

$$E_c(t) = \sqrt{2P_{oc}}\exp[j\{w_c t + f_{XPM}(t)\}] \quad (4)$$

where $P_{oc} = P_c\exp(-aL)$, P_c is the converter signal power at the fiber input. If the impulse response of the FP filter is represented by $h_{fp}(t)$, then the signal at the output of the FP filter can be written as

$$\begin{aligned} E_{ocf}(t,t) = \sqrt{2P_{oc}h_1}\int_{-\infty}^{\infty} &\left\{\cos\left[w_c t + \tfrac{1}{2}\Delta f_{XPM}(t_1,t)\right]\right\}\times\cos[w_c(t_1 - t/2) + \tfrac{1}{2}\{f_{XPM}(t_1) \\ &+ f_{XPM}(t_1 - t)\}]\times h_{fp}(t-t_1)dt_1 + E_{0ASE}(t) \end{aligned} \quad (5)$$

where $D f_{XPM}(t_1,t) = [f_{XPM}(t_1) - f_{XPM}(t_1 - t)]$ represents the differential phase modulation at the output of the MZI, E_{0ASE} is the filtered amplifier's spontaneous emission (ASE) noise. If $S_c(w)$ represents the spectrum of the converted signal in presence of ASE at the output of FP filter, then converted signal power at the output of the FP filter is given by

$$P_{cs} = \frac{1}{2p} \int_{w_c - pB_{opt}}^{w_c + pB_{opt}} \left| S_c(w) \right|^2 dw \qquad (6)$$

where B_{opt} represents the 3-dB bandwidth of the FP filter. The conversion efficiency is defined as the converted signal power at the output of the FP filter per unit input power for the pump and converter signals and is given by $h_c = P_{cs}/(P_c P_s)$. The amount of crosstalk introduced during the wavelength conversion process can be defined as

$$P_{ct} = \frac{1}{2p} \int_{w_c + 2pD_{ch} - pB_{opt}}^{w_c + 2pD_{ch} + pB_{opt}} \left| S_c(w) \right|^2 dw \qquad (7)$$

where D_{ch} is the channel separation between two adjacent channel.

4. Results

Following the theoretical analysis, the conversion efficiency per mili-watt of input power is determined for normal fiber at a bit rate of 10 Gb/s with 10 dBm input for pump and probe signals and is shown in Fig. 2. It is observed that efficiency of conversion is maximum at $D\,l = (l_c - l_s) = 0$ corresponding to maximum XPM coupling between the input signal and probe signal. Due to the effect of walk-off, the efficiency of conversion decreases with increase in $D\,l$. It is evident from the plots that conversion over a wavelength separation approximately 10 nm is possible without significant reduction in conversion efficiency. It is also noticed that conversion efficiency is higher for higher fiber length and for smaller values of delay time τ due to a larger bandwidth of MZI which allows more signal to appear at the output of FP filter.

The plots of wavelength converted signal power at the output of the optical filter are shown in Fig.3 as a function of the normalized optical filter bandwidth B_{opt}/B_r for wavelength separation $D\,l$=0nm, 1nm, and 2nm for conventional SMF and DSF of length 2 km. It is noticed that DSF provides better output power compared to conventional SMF at a given value of $D\,l$ and B_{opt} due to higher conversion efficiency. The variation of crosstalk with the normalized channel separation D_{ch}/B_r is depicted in Fig.4. As in the case of signal power, crosstalk power is also found to be higher in magnitude for DSF compared to conventional SMF. However, crosstalk can be greatly reduced by increasing the channel separation. The minimum required channel separations to have crosstalk below –30 dBm are found to be $4.75\ B_r$ and $6.25\ B_r$ for conventional SMF and $5.5\ B_r$ and $6.5\ B_r$ for DSF corresponding to $D\,l$=0 nm and 1 nm respectively.

The plots of signal to crosstalk ratio (SCR) at the output of the FP filter versus normalized optical filter bandwidth B_{opt}/B_r are shown in Fig. 5 for converter using conventional SMF. It is noticed that SCR decreases sharply with increase in optical filter bandwidth at a given $D\,l$ due to increased amount of crosstalk at higher filter bandwidth. To achieve a given value of SCR, there is a maximum allowable filter bandwidth. For example, for a given value of SCR=6 dB, the maximum allowable filter bandwidth is found to *be* $0.8\ B_r$, B_r, $2.2\ B_r$ corresponding to $D\,l$=0 nm,1 nm, and 2 nm respectively.

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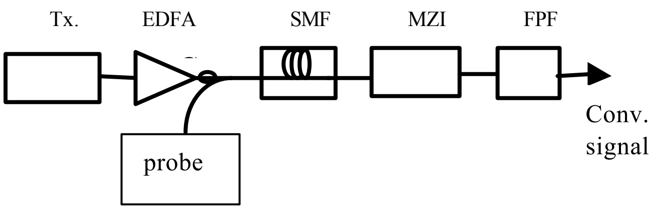

Fig. 1 Block diagram of a wavelength converter based on XPM in SMF and MZI

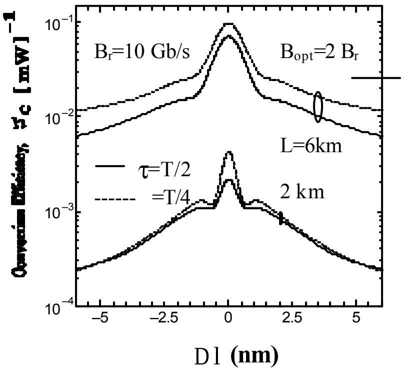

Fig.2 Wavelength conversion efficiency versus wavelength separation between the pump and probe for normal fiber with D_c=16.4 ps/km-nm.

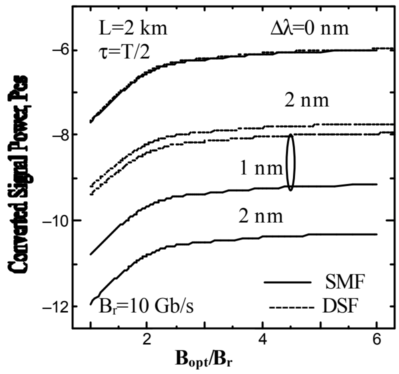

Fig.3 Variation of converted signal power with FP filter bandwidth normalized by bit rate.

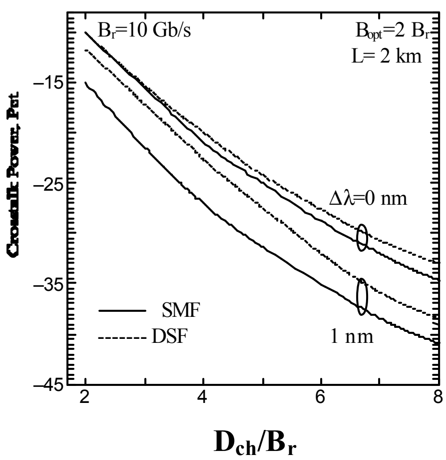

Fig.4 Variation of crosstalk power with the normalized optical channel separation for SMF and DSF.

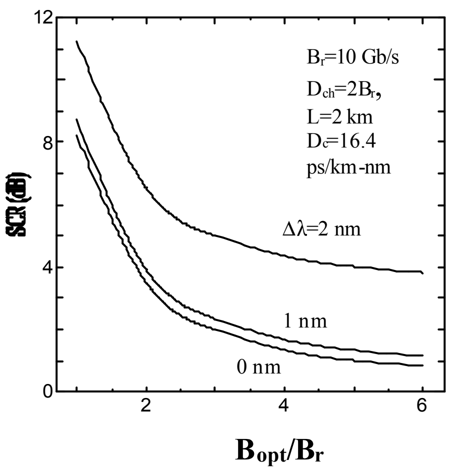

Fig.5 Plots of signal power to crosstalk power ratic at the output of FP filter as a function of normalized optical filter bandwidth.