Optik 113, No. 12 (2003) 541–547

http://www.urbanfischer.de/journals/optik

Optik Optics
International Journal for Light and Electron Optics

Performance analysis for an all-optical wavelength converter using four-wave mixing (FWM) in a single mode fiber

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Abstract: An analytical approach is presented to determine the performance of a tunable wavelength converter based on four wave mixing (FWM) in a single mode fiber (SMF) with two pump lasers. The analysis is carried out for an intensity modulated (IM) signal taking into considerations the effects of spectral broadening due to FWM and laser phase noise. The results evaluated at a bit rate of 10 Gb/s show that the signal power is substantially higher at lower values of wavelength separation. For example, for input powers of 10 mW each, wavelength separation of 4 nm between the pump-2 and the input signal, the output converted power is found to be −10 dBm corresponding to wavelength separation of 2 nm between pump-1 and converter signal. The corresponding crosstalk power is found to be −25 dBm at a channel separation of 3 times bit rate.

Key words: Wavelength converter – four-wave mixing – single mode fiber

1. Introduction

Optical wavelength conversion may play an important role in future multiwavelength optical network nodes to increase the network accessibility and flexibility and to reduce the blocking probability [1–3]. The wavelength converters are expected to convert one or more of the incoming wavelengths of a wavelength division multiplexed signal to a desired wavelength or group of wavelengths without significant distortion in the output signals and to facilitate wavelength reuse in an optical network node.

Out of the different wavelength conversion schemes, the most straight forward way is the opto-electronic conversion using either a direct detection or an heterodyne receiver and a transmitter [3]. However, this method does not provide efficient conversion of wavelength due to energy conversion from optical to electrical and vice-versa. As a consequence, all-optical wavelength conversion is very much attractive due to higher efficiency and fast response. Various techniques for all-optical wavelength conversion are reported in literature making use of the nonlinear characteristics of semiconductor lasers and amplifiers and of fibers. Using semiconductor lasers and amplifiers, wavelength conversion can be achieved by using cross-phase modulation (XPM) [4–5], cross-gain modulation (XGM) [6–7] and four wave mixing (FWM) [8–11]. On the other hand, single mode fibers can be used as a wavelength interchanger using the nonlinearity due to FWM [12–14].

The influence of FWM on optical WDM transmission has been investigated during the last few years [15, 16, 18]. Recently, the effective use of FWM for wavelength conversion results of wavelength conversion are also reported [8–14, 17]. Previous results using four wave mixing (FWM) in semiconductor optical amplifiers are focused on the efficiency of conversion and noise characteristics. For converters using FWM in fiber, theoretical results are reported on optical intensity modulated signal and was not include the spectral spread of the signal due to modulation, FWM process and non-zero linewidth of the signal and pump lasers. Further, the amount of crosstalk induced by the converted output light due to wavelength conversion in fiber converter is yet to be reported.

In this paper, we provide an analytical approach to determine the performance of an wavelength converter using FWM in SMF for wavelength conversion around the zero dispersion wavelength taking into considerations the spectral spread of the signal spectrum due to non-zero linewidths of the pump and transmitting lasers for a given modulation format. The analysis also includes the evaluation of crosstalk induced by the converter during conversion and the influence of total linewidth broadening due to transmitting and pump lasers [17]. The performance results are evaluated at a bit rate of 10 Gb/s and are presented in terms of output signal power, output signal to crosstalk ratio for different fiber and system parameters. The effects of optical filtering on the crosstalk performance are also investigated.

Received 25 October 2002; accepted 28 December 2002.

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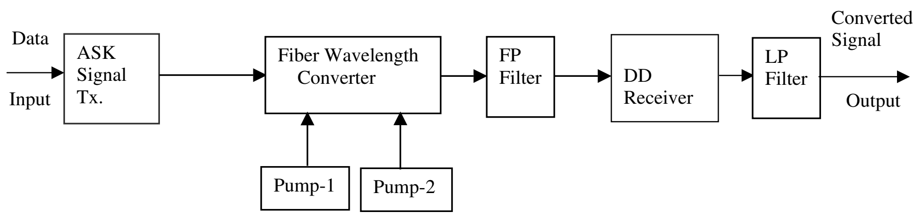

Fig. 1. Block diagram of a tunable wavelength conversion scheme based on four wave mixing in a single mode fiber.

2. Wavelength conversion scheme

The block diagram of the wavelength converter using FWM in single mode fiber is shown in fig. 1. The modulated signal and two pump lights are launched into the conversion fiber which has zero dispersion at $\lambda_0 = 1.3\ \mu$m and have frequency f_s, f_{p1} and f_{p2} respectively. The frequency of the generated FWM light at the output of the fiber is $f_c = f_{p1} + f_s - f_{p2}$ satisfying the phase matching condition of $(f_{p1} - f_0) = -(f_s - f_0)$ such that a change in f_s will produce a change in f_c. On the other hand, for a given signal frequency f_s, frequency conversion at any frequency f_c is possible by changing the frequency of the pump-1 or pump-2 signals [12, 14]. The relative positions of the input signal, pumps signals and the converted signal about the zero dispersion wavelength λ_0 are shown in fig. 2. Each of the distances of the pump-1 and the input signal from λ_0 is equal to $\Delta\lambda_1$ whereas that of pump-2 and converted signal is equal to $\Delta\lambda_2$.

3. Theoretical analysis

The optical signals input to the wavelength converter consists of the intensity modulated (IM) signal transmitted from transmitter and two pump signals form two local oscillator lasers. The IM signal at a wavelength λ_s can be represented as

$$E_s(t,z) = \sqrt{2P_s}\exp\left[\mathrm{i}\omega_s t + \mathrm{i}\phi_{ns}(t)\right] \times \exp\left(-\alpha z/2 - \mathrm{i}k_s z\right) \quad \text{‘Mark’} \tag{1a}$$

$$= 0 \quad \text{‘Space’} \tag{1b}$$

where P_s is the signal power, ω_s is the angular frequency of the optical carrier, c is the velocity of light in vacuum, $\Phi_{ns}(t)$ represents the random phase noise of the transmitting laser, α is the fiber attenuation coefficient, z is the propagation direction in the fiber, and k_s is the propagation constant at an angular frequency ω_s.

The two pump signals viz. pump-1 at a wavelength λ_{p1} with power P_{p1} and pump-2 at a wavelength λ_{p2} with power P_{p2} can be expressed as

$$E_{p1}(t,z) = \sqrt{2P_{p1}}\exp\left[\mathrm{i}\{\omega_{p1}t + \phi_{n1}(t)\}\right] \times \exp\left(-\alpha z/2 - \mathrm{i}k_{p1}z\right) \tag{2}$$

$$E_{p2}(t,z) = \sqrt{2P_{p2}}\exp\left[\mathrm{i}\{\omega_{p2}t + \phi_{n2}(t)\}\right] \times \exp\left(-\alpha z/2 - \mathrm{i}k_{p2}z\right) \tag{3}$$

where ω_{pi} and k_{pi} represent the angular frequency and propagation constant for the i-th pump signal respectively, and $\Phi_{ni}(t)$ is the random phase noise due to the non-zero linewidth of the pump laser source.

The Fourier amplitude of the i-th electric field spectrum of the i-th signal can be expressed as

$$E_i(\omega_i,z) = \tfrac{1}{2}F_i(\omega_i,z)\exp\{-\alpha z/2 - \mathrm{i}k_i z\} + \tfrac{1}{2}F_i^*(\omega_i,z)\exp\{-\alpha z/2 + \mathrm{i}k_i z\} \tag{4}$$

where the subscript i refers to s, $p1$, $p2$ for input signal, pump-1 and pump-2 respectively, and $F_i(\omega_i, z)$ is a complex spectral lineshape function which at $z = 0$ represents the input light spectrum for the i-th signal.

The three input signals propagating through the fiber generate difference frequency changes by the three wave mixing process due to nonlinear susceptibility of single mode fiber. Due to the finite spectrum of the input signals, the generated signal will have a finite spectral width. Due to the generation of new frequencies as the signals propagate through the fiber, there will be spectral broadening of the wavelength converted signal generated by four wave mixing. Since the four wave mixing is a nonlinear process, the change in spectrum of the wavelength converted signal can be determined by dividing the fiber length L into small segments of length ΔL over which the z-dependence

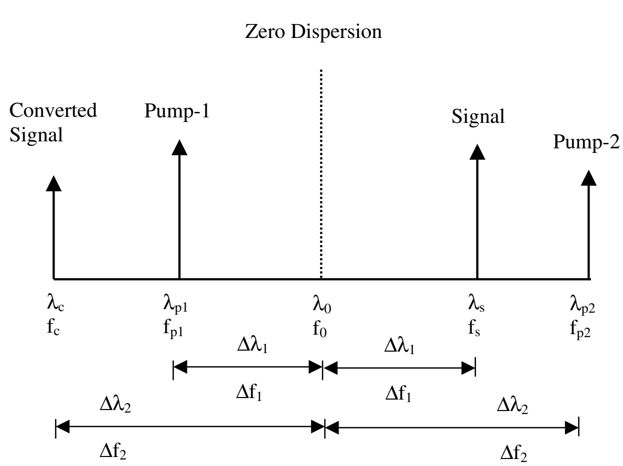

Fig. 2. Relative positions of the carrier wavelengths (frequencies) of the input signal, two pump lasers and the output converted light.