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Mach–Zehnder interferometer concatenated fiber loop mirror based gain equalization filter for an EDFA

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ABSTRACT

An all-fiber interferometric technique for gain flattening of amplitude spontaneous emission (ASE) response of an erbium doped fiber amplifier (EDFA) is presented. In the proposed method, a single-stage Mach–Zehnder interferometer (MZI) is cascaded to a fiber loop mirror configuration with polarization controllers incorporated inside the loop. By the mean of variation in polarization controller's orientation and number of fiber loops in it, it is possible to tune and modify the sliced wavelength spectrum of a single-stage MZI for achieving equalization of the EDFA gain spectrum. The present scheme has many advantages for being low loss, polarization independent, easy to tune and is demonstrated through simulation study and verified by experiments. The flattened ASE gain spectrum of an EDF over wavelength range of 35 nm with peak to peak difference of ± 0.4 dB is obtained.

1. Introduction

The growth of incessant demand for more and more capacity of data communication over a long haul optical link, leads to development of dense wavelength division multiplexed (DWDM) communication networks. An erbium doped fiber amplifier (EDFA) is an integral component of any typical DWDM optical link in C-band [1]. However, amplitude spontaneous emission (ASE) spectrum of a typical EDF is a non-uniform function of wavelength and a flat wavelength response in C-band is desirable for a more efficient communication link. An equalized gain over a range of 30 nm in C-band empowers the link to communicate with increased number of channels, and thus, ameliorating the spectral efficiency of the network. Many schemes have been proposed for flattening the response of EDFA [2–10]. Polarizations maintaining fiber (PMF) fiber or over coupled coupler based loop mirror configuration [4,5] successfully flattened the EDFA spectrum over a range of 30 nm. Nevertheless, these techniques suffer from high insertion/excess losses due to splicing between PMF and single mode fiber (SMF) or the use of over coupled coupler. Long period fiber grating (LPG)/fiber Bragg grating (FBG) based methods [8–10] for EDFA gain equalization has the drawback of polarization dependent filtering action. Inherent wavelength filtering action in specially designed fibers [2] is also generally not very cost effective solution and there exists a possibility of higher splice losses etc. In addition, they require specially designed fibers. Recently, Mach–Zehnder interferometer (MZI) based thermally tunable gain flattening technique employing planar light wave circuit (PLC) platform was proposed [7] wherein the needed requirement on delay length mismatch was very strict and it was thermally tuned. Through the present paper, a more suitable all-fiber, low loss, polarization independent scheme has been presented. In the proposed technique, an all-fiber single-stage MZI is configured to achieve wavelength filtering action and output port of the MZI is cascaded to a fiber loop mirror (FLM) so as to tune the free spectral range (FSR) and notch of the MZI's sliced spectrum in accordance with the need of flattening the ASE response of an EDFA in the C-band. In this scheme, the stringent/precise requirements on the values of FSR and wavelength notch (of the MZI) are waived off due to alternate tuning produced by the mean of polarization controllers incorporated in the loop of FLM configuration. In the recent times, fiber loop mirror configuration has been also employed for developing multi-wavelength fiber lasers [11] by incorporating PMF in the loop.

2. Methodology

It is well known that the spectral response of a single-stage MZI is dependent on phase mismatch/delay between its two arms. Depending on the relative phase suffered by the signal wavelengths while traversing through the delay line, some of the wavelength signals will appear at the throughput port and the complementary wavelengths will emanate from the coupled port. The spacing between two consecutive wavelengths of the sliced response at one of the output port of the MZI is expressible as [12]

$$\Delta\lambda = \frac{\lambda_1 \lambda_2}{(n_{\mathrm{eff}} \Delta l)} \tag{1}$$

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There are two requirements for achieving the gain equalization of EDFA over a range of 30 nm. These are mentioned as (1) the FSR of the wavelength filter/slicer should be greater than 30 nm and (2) notch of the wavelength filter response should be tuned to compensate the gain peak/hump in ASE response of an EDFA around 1530 nm. The first requirement is met by the single-stage MZI and second requirement of precise wavelength notch tuning can be obtained through polarization controllers inserted inside the FLM configuration. The spectral response characteristics of fiber Sagnac interferometer/FLM configuration can be modeled by replacing the loop with equivalent wave plate having retardation (φ) and orientation angle (θ) [13,14]. The origin of retardance φ and angle θ can be traced in bends and twists present in the fiber loop forming the Sagnac interferometer. If the orientation angle of the hypothetical wave plate is zero, then the interferometer will act as a mirror and the retardation has no effect on the light traversing the loop. This particular characteristic of FLM configuration has been proposed by Mortimore in developing an all-fiber laser [13]. Later, Morishita [14] exploited the same effect in tuning the wavelength response of an over-coupled fiber coupler. Further, Kumar et al. [5] also employed the over-coupled coupler in forming the loop mirror configuration and flattened the gain spectra of an EDFA. Based on this understanding, the output of a single-stage MZI is connected to the FLM configuration with polarization controllers incorporated in the loop for developing an all-fiber gain flattening concept. The topology is shown in the figure given below.

The mathematical expression for the light output emanating from the transmittance and reflectance port of the FLM cascaded with MZI (shown in Fig. 1) is written as [12–14]

$$P_t=\frac{1}{2}\left\{\left(S_3^4-2C_3^2S_3^2+C_3^4\right)J_{XX}^2[P_{MZ-S}]+2\left(S_3^4+2C_3^2S_3^2+C_3^4\right)J_{XY}^2[P_{MZ-S}]+\left(C_3^4-2C_3^2S_3^2+S_3^4\right)J_{YY}^2[P_{MZ-S}]\right\} \quad (2)$$

where $C_i=\cos(\kappa z)$, $S_i=-j\sin(\kappa z)$, $i=1, 2, 3$, κ is the coupling coefficient and P_{MZ-S} represent the power emerging from the MZI at the straight through port.

$$P_{MZ-S}=C_1^2C_2^2-2C_1C_2S_1S_2\cos\Delta\Theta+S_1^2S_2^2 \quad (3)$$

$\Delta\Theta$ denotes the phase difference due to the extra path length Δl between the arms of the MZI
where

$$J_{XX}=e^{j\varphi}\sin^2\theta+\cos^2\theta,\quad J_{XY}=J_{YX}=\left(e^{j\varphi}-1\right)\sin\theta\cos\theta,\quad J_{YY}=e^{j\varphi}\cos^2\theta+\sin^2\theta,$$

J_{XX}, J_{YY} and $J_{XY}=J_{YX}$, are the Jones matrices of order 2×2 of the waveplate [13,14].

The expression for the power at the reflected port is given by

$$\mathrm{Pr}=\frac{4C_3^2S_3^2}{2}J_{XX}^2[P_{MZ-S}]+\frac{4C_3^2S_3^2}{2}J_{YY}^2[P_{MZ-S}] \quad (4)$$

In the proposed configuration, even with MZI having FSR in the range of 30–150 nm, it is possible to achieve gain flattening of EDFA. In addition, the notch of the sliced spectral response of MZI may vary from 1520 nm to 1540 nm. The FLM configuration with polarization controllers is capable of compensating the variations in FSR and notch position of the filter. These two features of the proposed scheme, make it a very desirable configuration as it is in all-fiber form with couplers are the basic building blocks which are generally polarization independent and low loss widely available components.

3. Simulation studies

The expression for power emanating from the throughput port of a single-stage MZI is written in Eq. (3) and the output wavelength response of the MZI, formed by fiber couplers of different values of splitting ratio, is depicted in Fig. 2. It can be observed that sliced wavelengths would undergo different losses depending on the splitting ratio of the couplers. Since, a typical EDFA has a gain hump of about 6–8 dB, therefore and for gain equivalence, it is advisable to choose splitting ratios of the couplers forming the MZI so that the peak to peak power difference in the output spectrum is ~4–6 dB. The 2 dB spectrum manipulation can be obtained through FLM configuration by mean of polarization controller's appropriate orientation alignment.

Tuning of the MZI spectrum through FLM configuration is illustrated in Fig. 3. Here, MZI throughput is connected to FLM configuration realized by 5 dB coupler, with polarization controller (PC) inserted between the path of clockwise (CW) and counter

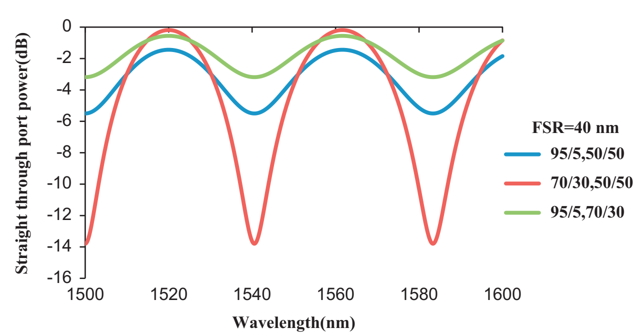

Fig. 2. Simulated response of single stage MZI at the straight through port for different values of splitting ratios of the constituent couplers.

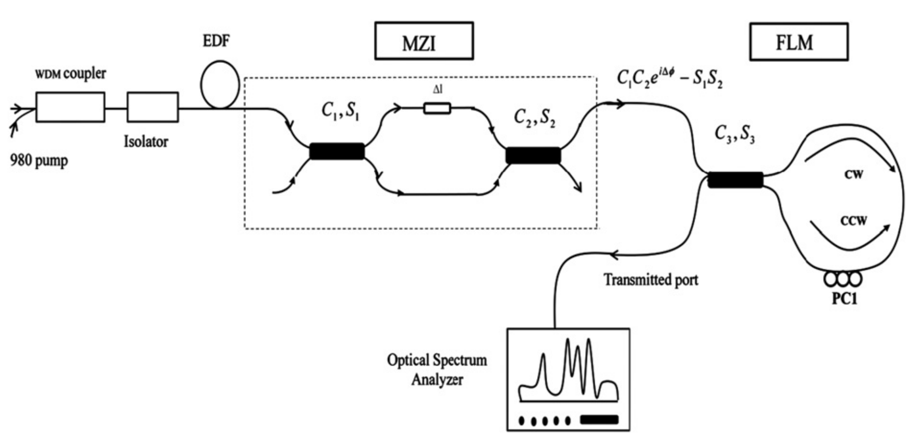

Fig. 1. A single-stage MZI cascaded FLM configuration with polarization controller incorporated in the fiber loop.