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Regular Articles

Miniaturized MMZI concatenated FLM for gain equalization of ASE response of an EDFA

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ABSTRACT

A miniaturized micro Mach-Zehnder interferometer (MMZI) has been employed, for the first time, for gain equalization of amplified spontaneous emission spectrum of an erbium doped fiber. An all-fiber MMZI with interference length of ∼1.5 cm, free spectral range of 40 nm, extinction ratio of 8 dB, and the total length of ∼5 cm, was indigenously realized. The interferometer was concatenated inside/outside the fiber loop mirror, with a built-in polarization controller. By appropriately adjusting the retardance and orientation angle of the polarization controller, the amplified spontaneous emission response of an erbium doped fiber has been flattened over the wavelength range of 35 nm with a peak to peak difference of ±0.46 dB.

1. Introduction

Optical fiber nano and microwires have the potential of miniaturizing the designed all-fiber devices for applications such as resonators [1], supercontinuum generation [2], trapping of atoms [3], three-dimensional solar cells, etc. [4]. Recently, a biconical fiber taper [5–7] based novel micro Mach-Zehnder interferometer (MMZI) configuration has been reported for diverse applications namely estimation of direct current, refractive index, curvature, and simultaneous measurement of strain, and temperature, etc. [8,9]. The MMZI can be realized by concatenation of two non-adiabatic fiber tapers, separated by a few centimeters long single-mode fiber without the plastic jacket. The major advantage of the MMZI configuration lies in its stable spectral response due to traversal of the different modes/beam through the same arm length. Perceptibly, MMZI can be considered among the categories of all-fiber wavelength filters like long-period fiber gratings (LPFGs) [11], fiber Bragg gratings (FBGs) [12], MZIs [13,14], fiber couplers/tapers [1,15], cascaded Hi-Bi fibers [16], Sagnac interferometers [15–18] etc. The above mentioned all-fiber devices have also been employed as gain equalization filter for flattening the gain spectrum of an erbium doped fiber amplifier (EDFA). Though, some of the all-fiber interferometer based filters have been successfully marketed for their diverse applications, including gain flattening of EDFA, nevertheless, there exist some drawbacks in the designs/schemes based on the existing all-fiber interferometers. Recently, fiber loop mirror (FLM) concatenated interferometers were employed in tailoring the spectral response of the wavelength filters for flattening the amplified spontaneous emission (ASE) spectrum of an EDF over a range of 30 nm by employing polarization maintaining fiber (PMF) [15] and over coupled coupler based loop mirror configuration [16]. But, these methods suffer from high insertion/excess losses due to splicing between PMF and single mode fiber (SMF) or the use of over coupled coupler. Fiber gratings (either LPG or FBG) based approaches [19,20,21], for EDFA gain equalization, has the drawback of polarization dependent filtering action. Inherent wavelength filtering action in specially designed fibers [22,23] is also usually not the very cost effective solution due to requirement of special fibers, and there occurs a probability of higher splice losses, etc. Further, MZI based flattening scheme in planar lightwave circuit (PLC) platform was also suggested [24] wherein the required requirement on delay length mismatch was very strict, and it was thermally tuned. In addition, the MZI based schemes suffer from random fluctuations in their spectral response. In the present proposed method, an all-fiber MMZI is cascaded with an FLM so as to tune the free spectral range (FSR) and the notch of the MMZI's sliced spectrum in accordance with the need of flattening the ASE response of an EDF in the C-band. In this scheme, the stringent/precise requirements on the values of FSR and wavelength notch (of the MMZI) are waived off due to alternate fine-tuning produced by polarization controllers incorporated in the loop of the FLM configuration.

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2. Methodology

Irrespective of the method of EDFA gain flattening, there are two necessities 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 positioned to compensate the gain peak/hump in ASE response of an EDFA around 1530 nm. The first condition can be met by the MMZI. And for satisfying the second condition, it can be cascaded to the FLM configuration with polarization controllers incorporated in the loop. For the first time, authors are reporting gain compensation of ASE of an EDF through the usage of MMZI configuration comprised of two non-adiabatic fiber tapers. The down tapered section of the first fiber taper remains single mode, with only LP_{01} mode traversing through it, till its V parameter becomes ~0.84 [25,26]. Afterward, the effect of the core becomes negligibly small, and fiber modes are predominantly guided through the cladding (as core) with air playing the role of the cladding. Under this condition, the general local fiber modes such as LP_{01}, LP_{02} and other higher order modes gets excited and traverse through the taper. Nevertheless, the most of the power initially contained in LP_{01} modes gets coupled with LP_{02} mode and power possessed by higher order modes is relatively small [9,26,27]. Since Jacket of the cladding had been removed, the cladding modes would also travel as guided modes through the distance (also called interference length (L)) between the two tapered sections of the MMZI. As these modes propagate with different propagation constants through the interference region, the accumulation of phase difference leads to the beating phenomenon among them. The superposed fields enter the second tapered section and undergo mutual coupling resulting in the creation of the interference fringes as MMZI spectral response (see Fig. 1). The FSR of the interference pattern is decided by the length of the interference length, whereas the depth of interference fringes is governed by the coupling coefficients/steepness in the tapered sections. The well-known relation, for the FSR, by assuming interference between LP_{01} and LP_{02} modes only, is given below [10,26,28,29].

$$\Delta\lambda = \frac{\lambda^2}{L\Delta n_{eff}} \tag{1}$$

where Δn_{eff} is the difference in effective indices of the fiber modes LP_{01} and LP_{02}

According to Eq. (1), FSR of MMZI spectral response strongly depends on the length of the interference region and difference between the effective indices of the LP_{01} and LP_{02} modes. Since, the effective indices of the different modes of the fiber, with known characteristics parameters, can be estimated, thus, by adjusting the suitable interference length and coupling strength/taper steepness, a wavelength filter with FSR 30 nm and extinction ratio more than ~6 dB can be fabricated. Subsequent, the remaining desired requirement for precise wavelength notch tuning can be obtained by FLM configuration with built-in polarization controllers. The theoretical spectral response of fiber Sagnac interferometer/FLM configuration can be simulated by replacing the bends and twists in the fiber loop with equivalent wave plate [30,31] having and angle of orientation θ and offering retardance φ 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 would have no effect when the light is traversing the loop. In the present paper, two configurations having MMZI connected outside and inside the loop of FLM configuration are considered for flattening the ASE of the EDF. The schematics of the experimental set-up for both configurations are shown in Figs. 2 and 3. The mathematical expressions for the transmitted power (P_t) emanating out of port 2 of the FLM, corresponding to schematics shown in the Figs. 2 and 3, are written as in Eqs. ((2) and (3)) [18].

$$P_t = (X_{filter}(\lambda))\left\{\left(S_1^4 - 2S_1^2C_1^2 + C_1^4\right) + 4S_1^2C_1^2\sin^2 2\theta \sin^2\frac{\phi}{2}\right\} \tag{2}$$

$$P_t = (X_{filter}(\lambda))\left\{\left(S_1^4 - 2S_1^2C_1^2 + C_1^4\right) + 2S_1^2C_1^2\sin^2 2\theta \sin^2\frac{\phi}{2}\right\} \tag{3}$$

where *X filter(λ)* is the wavelength filter function (it represents the spectral response of MMZI here), and S_1^2: C_1^2 is the splitting ratio of the coupler forming FLM.

The difference between Eqs. (2) and (3) is the presence of numeral 4 multiplied with sine terms (see Eq. (2)) instead of numeral 2 multiplied with sine terms (see Eq. (3)). The presence of extra factor 2 makes it easier, to manipulate the filter response, in the sense that less amount of retardation (number of loops of fiber) are required to create similar effect as achieved from the other configuration.

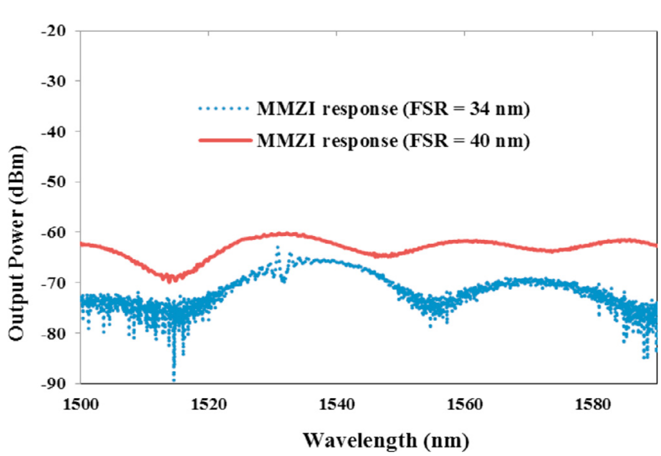

Fig. 1. Spectral responses of two MMZI samples were having FSR 34 nm & 40 nm for two different interference length 2 cm and 1.5 cm, observed on OSA.

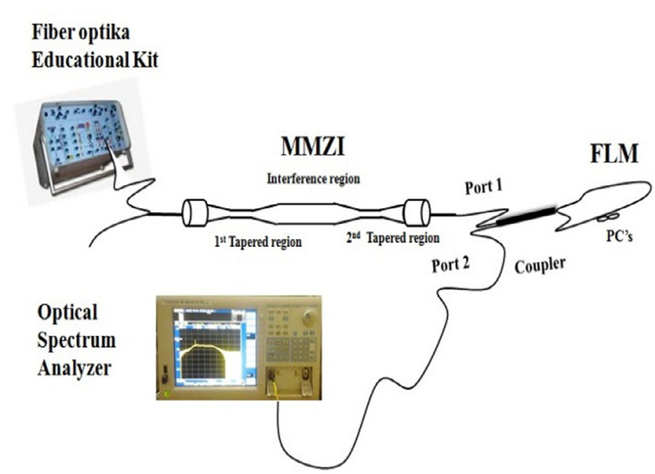

Fig. 2. Schematic of the experimental setup having a single-stage MMZI outside the FLM configuration with polarization controller inbuilt in the fiber loop for the gain flattening of EDF spectrum.