In-Line Fiber Tunable Pulse Compressor using PM-Mach Zehnder Interferometer

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ABSTRACT

Narrow laser pulse is an essential part of rapid optical communication system utilizing high channel capacity. In this study, a dynamic simulation model was developed using a multi-physics Comsol version (5.5), to evaluate the performance of a tunable narrow pulsed laser source by using polarization-maintaining fiber to build an Inline Mach-Zehnder fiber interferometer (PM-MZI), whereas three variable-lengths of single-mode polarization maintaining fiber (8,16,24) (cm) spliced between two segments of (SMF-28) with (26,13 cm) length respectively after propagation of 10 (ns), 1546.7(nm) and 1.22(mW) pulsed laser. A tunable interferometer was implemented by applying mechanical forces on the cross-sectional area of the PM fiber and the two splicing regions to change the interference cavity length. The value of compression factor was obtained 1.103 of 1610 (nm) central wavelength under the effect of 20 (g) applied on 16 (cm) PMF cross-sectional area.

KEYWORDS

In-line Mach-Zender Interferometer, Polarization Maintaining Fiber, Pulse compression, compression factor, FWHM, Peak power.

INTRODUCTION

Dispersion is one of the optical communication signal problems that causes signal distortion [1]. This simulation work provides a novel design of dispersion-mitigated inline fiber interferometer using polarization-maintaining fiber (PMF) spliced between two single-mode fibers (SMF) after propagation of 10 (ns), and 1.22(mW) pulsed laser, was designed by using an electronic chopping circuit to change the output of CW laser diode to train of pulses[2]. The interferometer was subjected to different mechanical forces to compress the optical pulse out from the interferometer and develop a low cost, narrow optical communication source. Recently Panda-type PM fibers have dominated on most of applications because of its flexible and compatible with regular telecommunication optical fibers [3].There are many advantages of using inline fiber interferometers in communications, optical modulation, pulse compression [1-5], and sensing applications due to their ability to measure different parameters such as pressure, force, strain, temperature, etc.[6], along with having high sensitivity, immunity to electromagnetic interference and simple structure [7,8]. The in-line fiber Mach-Zehnder interferometer is considered as significant interferometer among the recently investigated interferometers because of its good coupling efficiency, compactness, and easy implementation capabilities [9,10]. Mathematical modeling and characterization of inline fiber interferometer are crucial to select the exact parameters for a specific application and predict the effect of the surrounding environment on those interferometers [5,8].

In (2018), Sura Hussein; ...et. al. implemented a pulse compressor using a tunable hybrid Mach-Zehnder interferometer made from 7 and 19 cell hollow-core photonic crystal fibers after applying mechanical forces along the fiber cross-sectional area to obtain compression factor (FC) equal to 2 and 4 for 7 and 19 cell hollow-core photonic crystal fiber(HC-PCF) respectively[11]. Ali A. Dawood; ...et. al. used 7 and 19 cells HC-PCF to build a Mach-Zehnder interferometer, but they replaced the fibers’ air holes by 25% acrylic acid diluted with 75% ethanol and managed to achieve FC= 4.9 [12]. Nowadays, new type of interferometer was designed using all fiber micro cavity Mach-Zender interferometer and the cavity region can be either air[13] or fiber spliced regions [14]. In this paper, we evaluated the performance of a tunable narrow pulsed laser source by using polarization-maintaining
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A PM-Mach-Zehnder interferometer was built by using three variable-lengths of single-mode polarization maintaining fiber (8, 16, 24) cm spliced between two segments of (SMF-28) with (26, 13) cm length respectively after propagation of 10 ns, 1546.7 nm and 1.22 mW pulsed laser. A tunable interferometer was implemented by applying mechanical forces on the cross-sectional area of the PM fiber and the two splicing regions to change the interference cavity length.

**THEORY**

Interferometers are mainly explained by superimposing two or more of the same frequency light beams and measuring the phase difference between them [1, 7]. The Mach-Zehnder interferometer generally consists of two or more separated arms of the same signal (i.e., optical signal) to be recombined; then the optical phase change between these arms is characterized using equation (1) [4, 9, 15]:

$$\Phi_{MZI}^m = \frac{2\pi \Delta n_{\text{eff}}^m L}{\lambda}$$

\[ (1) \]

where

- $\Delta n_{\text{eff}}^m$ is the effective refractive index difference between the core mode.
- $n_{\text{eff}}^m$ cladding mode.
- $L$ is the interaction length.
- $\lambda$ is the input wavelength.

The polarization properties of PMF is characterized by its birefringence $B$, which is calculated using equation (2):

$$B = \Delta n_{\text{eff}} = n_x - n_y$$

\[ (2) \]

The beat length is a measure of the length or period of the polarization evolution along PMF as a consequence of its birefringence [1]. This PMF split the optical signal into two beams; one travels along the fast axis, and the other travels along the slow axis of the PMF. Then they recombine in the second piece of SMF. The length of the PMF was estimated using the beat length equation (3), (4) [16, 17].

$$L_B = \frac{2\pi}{\Delta \beta} = \frac{\lambda}{B}$$

\[ (3) \]

$$L_B^o = \frac{\lambda}{\Delta N_{\text{eff}}}$$

\[ (4) \]

The narrower pulse in the time domain has the broader spectrum in the spatial domain is a very well-known concept in communications [1, 6, 16]. Therefore the figure of merit of this study is characterized by the compression factor; which is the ratio of input signal full width at half maximum to the output signal full width at half maximum [1].

$$Fc = \frac{\text{FWHM}_{ip}}{\text{FWHM}_{o/p}} = \frac{\Delta \omega_{\text{FWHM}_{ip}}}{\Delta \omega_{\text{FWHM}_{o/p}}}$$

\[ (5) \]

Temporal FWHM can be obtained from the spatial FWHM using the equation (6). [18, 19]:

$$\Delta t_{f} = \text{FWHM}_{\text{temporal}} = \frac{\lambda_c^2}{c \times \text{FWHM}_{\text{spatial}}}$$

\[ (6) \]

where:

- $\lambda_c$ central wavelength in nm.
- $c$ is the speed of light in vacuum.
Mechanical forces were used to tune the phase of the optical signal on one arm of the PM-MZI. The applied forces imposed a stress on the fiber which, in turn, caused elongation in the fiber. The amount of the fiber elongation can be calculated using equations (7)-(9) [17-20]:

\[ \text{the strain} = \frac{\Delta L}{L} = \frac{\text{stress}}{\text{young modulus}} \]  \hspace{1cm} (7)

\[ \text{stress} = \frac{\text{Force (N)}}{\text{Area (m)}} \]  \hspace{1cm} (8)

\[ F = m \times G \]  \hspace{1cm} (9)

where:

- \( L \) is the original length.
- \( \Delta L \) is the change in length.
- \( F \) is the force applied in (N).
- \( A \) is the cross-sectional area in (m²).
- \( m \) is the value of the standard weight mass used to induce mechanical force.
- \( G \) is the gravitational acceleration.

Young’s modulus is the modulus of elasticity ranges from 66 Gpa to 74 Gpa for the SiO2 i.e 70 GPa.

The mechanical forces in this work were done by applying different masses (0, 5, 10, 20, 50, and 100) (g) on the PMF. The young modulus for the optical fiber (i.e., SiO2) was evaluated using equation (10) [18]:

\[ E_{1} = 2.223 \times 10^{-6} (1 - P_{1}) \left( \frac{\rho}{1 - P_{1}} \right)^{3.108} \]  \hspace{1cm} (10)

**SIMULATION WORK**

To study and provide a clear vision about how optical signals propagate along optical fibers and affected by the outer environment changes, the COMSOL (version:5.5) software was used to simulate the PM-MZI of this work. Fig.1 (a) geometrical simulation build-up of PM-MZI using Comsol software (b) the material properties identification fiber core and clad. Shows the geometrical implementation of the interferometer.
Figure 1. (a) geometrical simulation build-up of PM-MZI using Comsol software (b) the material properties identification fiber core and clad.

The section of the material's refractive index value of both core and clad of the simulated SMF and PMF was based on standard fibers data sheet and previous studies [20,21]. The effective index resulted from fusion and splicing was calculated theoretically using the general form of effective index formula "the $n_{\text{eff}}$ is defined as the average of the refractive indexes of the constituents; i.e: $n_{\text{eff}} = (F_n a_1^2 + F_n b_2^2)^{1/2}$. Where F is the percentage fraction of constituting material fraction[22-24]. The self-image for boundary propagating modes analysis is recorded for each case separately. To simulate the effect of external induced force on PMF and splicing region equations (7-10) are used to find the elongation of fiber at each force separately the cross-sectional area of optical fiber has 125μm cladding is equal to [(62.5e-6)²×π =1.227e-8 m²].

RESULTS

The elongation for the cross section of PMF will be reducing of the geometric parameters of PMF, this change of parameters caused decreased the groove velocity for all modes which propagated through the core and cladding for the fiber and the reducing in parameters of fiber will be changed on the parameters of pulse that propagated through the fiber. The resulted of fiber elongation is presented in the figure (2).
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Figure 2. Elongation as a result of applied varies weights. (a) cross section area and (b) splicing regions

Narrow pulsed laser was obtained in the PM-Mach Zehnder interferometer when compared with other previous works that used empty hollow PCF-MZI or replaced all of its air holes with different materials. The boundary mode analysis results of PM-Mach Zehnder interferometer variation with force are shown in table of figures (1), (2) and (3) respectively. Since the narrower pulse in time domain can be gained from the wider pulse in spectral domain then the best compressed pulse in this study is gained from the highest propagation order mode. By observing following figure can see that the higher excitation of higher order modes came from the (16) cm PMF.

Table of figures 1. The simulation results of boundary mode that demonstration the mode distribution in bimodal interferometer of PM-MZI after applying different weights on the cross sectional area and splicing regions of the PM and SM fibers with PMF length (8 cm).

<table>
<thead>
<tr>
<th>weights</th>
<th>Forces applied on PMF</th>
<th>Forces applied on splicing region</th>
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<tbody>
<tr>
<td>0</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<td>5</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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Table of figures 2. The simulation results of boundary mode that demonstrate the mode distribution in bimodal interferometer of PM-MZI after applying different weights on the cross sectional area and splicing regions of the PM and SM fibers with PMF length (16cm).

<table>
<thead>
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**Table of figures 3.** The simulation results of boundary mode that demonstrate the mode distribution in bimodal interferometer of PM-MZI after applying different weights on the cross sectional area and splicing regions of the PM and SM fibers with PMF length (24cm).

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Figure(3) show the peak power of interferometer after applying mechanical forces on the micro cavity splicing regions and PMFs cross sectional areas. The highest peak power value was recorded result in the case of 24(cm) PMF when no force was applied on it. While the peak power in the other cases remained very low. One reason of getting very low power is the back reflection portion of incident light on input port of PM-MZI which was very high compared to transmitted one and absorption portion of light through fiber although the absorption has very small magnitude yet still can affect the small portion of propagating light after reflection at the entrance.
Figure 3. The peak power variation of PM-MZI with (8, 16, 24 cm) and different weights applied on the (a) cross sectional area and (b) splicing regions.

The results of the interferometer spectral width are very wide as shown in figure (4). So, these results promising to giving rise to the possibility of getting narrower temporal pulses for communication applications. The highest spectral width 161(μm) has been gained when the PMF was 16 cm length and 100(g) of weight was applied on the PMF cross-section area.
**Figure 4.** The Full Width Half Maximum variation of PM-MZI with (8,16,24cm) and different weights applied on the (a) cross sectional area and (b) splicing regions

**CONCLUSION**

The main points that can be concluded from this work are, the value of compression factor was obtained 1.103 of 1610 (nm) central wavelength under the effect of 20 (g) applied on 16 (cm) PM cross-sectional area. A high sensitive interferometer was obtained by the excitation to the high order mode which were characterized by visualized shifting to central propagating wavelength the PM-MZI. The narrow laser was obtained in this theoretical study because it is regardless the coupling and splicing loss just the PMF fiber interferometer cross-sectional area and elongation after applying mechanical forces were considered.

**REFERENCES**


