Temporal manipulation of light propagation via cross-intensity modulation in unbalanced fiber Mach-Zehnder interferometers

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Abstract: We theoretically propose and experimentally demonstrate an approach to achieve temporal manipulation of light propagation via cross-intensity modulation (XIM) effect in an unbalanced fiber Mach-Zehnder interferometer (MZI). By changing the optical loss indices (which can also be gain indices theoretically) discrepancy in the two branches of the MZI, we can obtain the largest time shifts at the minima of the transmission frequency spectrum, while there shows no time shifts at the maxima. This scheme provides a flexibility of ultra-wide bandwidth operation both on optical wavelength and modulation frequency.

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References and links

1. Introduction

Slow and fast light (SFL) effects have been extensively studied [1–5] in the past decades due to their potential applications in optical buffers [6, 7], microwave photonic filters [8, 9], switches and synchronizers [10], sensitivity enhancing [11, 12], etc. SFL effects are phenomena that light propagates in media or structures at low group velocity $v_g$ (slow light, $v_g < c$, $c$ is the speed of light in vacuum) or at a large group velocity (fast light, $v_g > c$ or negative). SFL effects usually result from the abrupt variation of the real part of the complex refractive index by creating a normal/anomalous dispersion [13, 14]. Meanwhile, a different kind of SFL effects has been found in structural media, in which no substantial material dispersion occurs. SFL are brought about by the structure features such as in photonic bandgap (Bragg gratings) systems. Structural SFLs has been detected in photonic crystals [15, 16], fiber Bragg gratings [17], and serial loop structures [18]. Not only in the optical range, structural SFLs can also be achieved in microwave, radiofrequency [19], and even acoustic wave packet can achieve group velocity beyond the speed of light [20]. A comprehensive analysis of these structural SFL systems was developed by Julia Arias and et al [21, 22]. Structural SFLs are of particular advantages, such as enhancing nonlinear effects [23, 24].

In addition, SFLs based on cross-gain modulation (XGM) were also found in different media [25–27]. In these systems, a controlling light is used to manipulate the signal light, but the operation wavelength and modulated frequency are limited due to the properties of the gain media. The SFL effect in MZI has been observed in coaxial cables [19, 21]. The superluminal and negative group velocity propagation was achieved by changing the carrier frequency or the length difference of the branches in the MZI in the radiofrequency (RF) range. In the optical range, theoretical study of SFL effects in silicon-based MZIs had been also reported [22]. The pulse time shifts are driven by the total attenuation of the system, which could be changed either by changing the attenuation coefficient of the medium in the branches or the interferometers’ size. Recently, we found an effect named cross-intensity modulation (XIM) in an unbalanced fiber MZI. Through tuning the optical loss or gain index in each arm, the pulse can be delayed or advanced. Unlike the method in [22], we simply
adjust the optical loss index in each branch of the MZI via a variable optical attenuator (VOA) but not the loss coefficient of the medium to achieve large delays or advancements.

In this paper, we analyze the principle of temporal control of light through optical loss in an unbalanced fiber-based MZI and then experimentally prove the proposal. By setting a length difference between the two arms of the MZI, we achieved the maximum time shifts at the transmission frequency minima, meanwhile no obvious shifts were observed at the transmission maxima. This scheme is simple and approachable for practical applications.

2. Theory

We consider a sinusoidally modulated light pulse propagating through an unbalanced fiber-based MZI, which is composed of two 50:50 couplers and single mode fibers (SMFs), as shown in Fig. 1. The lengths of the two arms are $L_1$ and $L_2$, respectively. The transmitted complex amplitude of the output pulse after the MZI can be expressed as:

$$\hat{A}_t = \sum_{i=1}^{2} E_i e^{-i\alpha_i} m_p e^{i\phi_i}$$

Fig. 1. Schematic of a fiber-based MZI and its phase relationship of the pulse between two arms.

where $E_i$ is the intensity split into each arm, $e^{-i\alpha_i}$ is the loss index ($e^{-i\alpha_i} < 1$) or gain index ($e^{-i\alpha_i} > 1$) through the $i_{th}$ branch (here, we discuss the mechanism in loss domain, i.e., $e^{-i\alpha_i} < 1$), $m_p$ is the modulation depth. The phase $\phi_i$ propagating along the $i_{th}$ branch is

$$\phi_i = \frac{n \omega}{c} L_i + \phi_0$$

Here, $f$ is the modulation frequency, and $\omega = 2\pi f$. $\phi_0$ is the modulation phase, $c$ is the light speed in the vacuum, and $n$ is the refractive index in each branch. $L$ and $\Delta$ is defined as

$$L = \frac{(L_1 + L_2)}{2} \text{ and } \Delta = L_2 - L_1$$

where, $L$ means the average length of the two branches, which is actually the effective length of the MZI. $\Delta$ is the length difference of the two branches. The parameter $\beta = n \omega \Delta / c$ describes the phase shift from the length difference $\Delta$. Therefore, the transmission spectrum is

$$|\hat{f}(\beta)| = \frac{A}{2} \sqrt{e^{-2m} + 2e^{-(m+1)} \cos(\beta) + e^{-2m}}$$

where, $A$ replaces $m_p \cdot E_i$. It can be seen that for the extrema of the transmission spectrum, the maxima match $\beta_{max} = 2m\pi$ ($m$ is an integer), the corresponding modulation frequency $f_{max} = c\beta_{max} / 2\pi n\Delta$, as for the minima $\beta_{min} = (2m+1)\pi$ and $f_{min} = c\beta_{min} / 2\pi n\Delta$. $|\hat{f}(\beta)|$ is symmetric with respect to $\alpha_1$ and $\alpha_2$. The same loss or gain happens on either arm leads to the same change of the transmission spectrum. Thus, the introduced loss does not change the
frequency position of the transmission extrema. In order to simplify the formula of the phase shift of the output pulse, two other quantities were defined as:

\[ \eta = \frac{(e^{-\alpha_1} - e^{-\alpha_2})}{2} \quad \text{and} \quad \zeta = \frac{(e^{-\alpha_1} + e^{-\alpha_2})}{2} \]  

(5)

which make contributions to the transmission coefficient and phase of the recombined pulse according to \( \hat{I} = A \cdot e^{j(\omega c + \theta_0)}(\zeta \cos(\beta / 2) + j\eta \sin(\beta / 2)) \). With recombination at the output port, the whole phase shift of the pulse after the MZ interferometer is:

\[ \varphi = \frac{\alpha_0}{c} L + \arctan\left[ \frac{\eta}{\zeta} \tan\left( \frac{\beta}{2} \right) \right] + \varphi_0 \]  

(6)

The time delay \( t_d \) introduced by the MZI is defined as \( \varphi / \omega \), which has the form as:

\[ t_d = \frac{L_n}{c} + \frac{\varphi_0 + \arctan\left[ \eta \tan(\beta / 2) / \zeta \right]}{\omega} \]  

(7)

In Eq. (5), \( \eta / \zeta \) can be changed within the range of \([-1, 1]\) by changing \( \alpha_1 \) and \( \alpha_2 \). Thus, \( t_d \) can be tuned through changing the optical losses on the two arms of the MZI. We introduce a parameter \( t_e = \arctan(\eta \tan(\beta / 2) / \zeta) / \omega \) as the time shift in Eq. (7). It is easily figured out that the largest time shift is achieved at the modulation frequency \( f_{\min} \), while no time shifts at \( f_{\max} \).

It should been noticed that in Eq. (7), \( t_d \) is a constant when \( \Delta = 0 \), whether we change the loss index or not. It is to say, there is no SFL effects in a balanced MZI. In Eq. (4), equal loss index or lossless in each arm will lead to zero delay at the minima. That’s why no SFL effect will occur, thus we change the loss index discrepancy to achieve SFL in our scheme.

### 3. Experimental setup

Figure 2 shows the setup in the experiment. The light from a tunable light source (TLS) at 1550 nm with a line-width of 40 MHz (the coherent length is about 5m) is sinusoidally modulated by a radio frequency generator (RFG) in an electro-optic modulator (EOM), then it propagates into an erbium doped fiber amplifier (EDFA) to be amplified. Polarization controller 1 (PC1) is to stabilize the polarization status as the EOM is polarization-dependent. The MZI is made of two identical 50:50 optical couplers. The lengths of the two arms are 11.18m and 5.2m respectively (with a length difference of 5.98m). The two digital variable optical attenuators (VOAs) are exploited to adjust the loss on each arm, and the insert losses of them are basically the same. The output light pulse after the MZI is then sent into a photodetector (PD) to transfer light into electric. The power meter is to monitor the power change. A 2 GHz oscilloscope triggered by the RFG is used to monitor the pulse shifts in time domain, and a vector network analyzer (VNA) is to measure the radio transmission spectrum.
4. Results and discussion

Figure 3 shows the transmission spectrums of the MZI under different losses. We set the modulation depth as 0.15, and the initial power into each arm is 9 mW. The loss index on the shorter arm is 0.44, and that on the longer arm is changed with the values labeled in Fig. 3. The lower x-axis shows the modulation frequency, the upper tells the phase shifts accordingly. The transmission spectrum does not shift horizontally by changing the loss on the longer arm, while the depth of each frequency varies and the depths of the frequencies close to the minima change even more intensely with the loss. When the loss indices on the two arms are the same, i.e. 0.44, the largest notch depth of the transmission minima is achieved.

Figure 3 shows that the transmission spectrum is periodic with a period of $2\pi$ in phase shifting, or 33.4 MHz in frequency. In our experiment, we choose a frequency period from 317.9 MHz to 351.3 MHz (comprise two minima and one maximum) under the same loss scheme as above to test the time delays or advancements.

Figure 4 shows the time shifts of output lights under different losses. We choose 318.5 and 351 MHz around the transmission minima and 334.5 MHz at the maximum as typical test points to reveal the time shift of the pulses. The loss index in the longer arm is tuned from 0.022 to 1. The loss index values were changed as the same as in Fig. 3. The loss index in the shorter arm is fixed at 0.44. The directions of the arrows show delays (backwards) or advancements (forwards) of the pulses. An advancement of 1.20 ns at 318.5 MHz, and a
delay of 1.21 ns at 351 MHz are detected, whereas almost no time shifts occur at the transmission maximum of 334.5 MHz. The results agree well with the theoretical prediction.

We choose several frequencies covering one period to tell the feature of the pulse in time domain under different losses. In Fig. 5(a), all lights under the chosen frequencies show a monotonous trend in time shifts along with loss changes. The time shifts change faster when loss index is less than 0.44 (smaller than the loss index on the shorter arm). When the loss index exceeds that of on the shorter arm, the time shifts change relatively slow. It is because the depths change more intensely when the loss index on the longer arm is smaller than 0.44, as seen in Fig. 3. These results match the features of Eq. (7). We notice that the direction of time shifting differs beside the transmission maximum. In our scheme, the advancements are of positive values and the delays are of negative values. This is decided by the sign of \( \eta \) and \( \tan(\beta/2) \). Thus, the pulse shows advancement at the lower frequency side of the transmission maximum of 334.5 MHz, while it shows delays for the higher frequency side. The reason is that \( \tan(\beta/2) \) is negative at the lower frequency side, and positive at the higher one.

Fig. 4. Transmitted light pulses and the time shifts around the transmission minima and maxima under different losses. The direction of the arrows shows the delay or advancement of the pulses.
Figures 5(b) and 5(c) depict the maximum time shifts and maximum fractional time shifts. The latter is the ratio of the time shift and the period of the modulation signal. The experimental results show a good agreement with the simulation. Figure 5 shows that the largest time shifts can be achieved at the transmission minima, and no evident time shifts occur at the transmission maxima. For each frequency $f$, the maximum time delay or advancement could be $\left(\frac{m}{f} - n\Delta/c\right)$ ($m = \beta_{\text{max}}/2\pi$, here $m = 10$). To achieve it, $\eta/\zeta$ should be tuned within the range of $[-1, 1]$ and by this loss scheme we actually tune $\eta/\zeta$ from 1 to $-0.4$. If we fix a larger loss on the shorter arm, we can infinitely approach the range of $[-1, 1]$. However, the maneuverability should also be considered.

From Eqs. (6) and (7), we deduce that, the delays or advancements could be contrary if the loss scheme on the two arms is reversed. Figure 6 gives a proof for this viewpoint (the loss on the longer arm is fixed at 0.44, the loss on the shorter arm varies).

With the analysis above, the optical loss on each arm will lead to a time shift of the pulse after the MZI. The split pulses from the two arms have a mutual intensity modulation effect when recombine at the output port. Thus, we name it as cross intensity modulation (XIM). Though the experiment is conducted with the uneven loss scheme, the same time shifts are achievable with gain scheme and adjusting the gain index discrepantly on each arm. In this way, time shifts and amplified signal can be simultaneously achieved. Compared with other SFL methods, our scheme is simple and with good operability. Though the fractional time shift is restricted within 0.5, we can cascade several schemes to achieve larger time shifts. Surely, it cannot be neglected that the transmission extrema are fixed for a settled length difference. However, for a certain modulation frequency, we could carefully design the length difference to make sure the desired frequency lies at the transmission minima so that large time shifts can be realized. Because the temporal manipulation here doesn’t results from the dispersion, this scheme has no obvious limitation of delay bandwidth product.
Compared with the XGM effect in gain media, due to the limitation of the metastable lifetime of the gain media, the modulation frequency of the signal light is restricted. The proposed XIM effect is based on the structure feature of the MZI, it does not have the limitations on the modulation frequency or operating wavelengths.

5. Conclusion

The temporal manipulation due to the XIM effect in unbalanced MZI has been realized. The maximum time shifts are achieved at the minima of the transmission frequency spectrum. This approach has the advantages of simplicity, low cost and controllability. It is most important that the operating wavelength can be extra wide owing to no limitation of gain band, and likewise, the modulation frequency is not limited. The time shifts is not dependent on the input power but on the loss or gain index, so the sensitivity of power change on the arms could be rather high. It may be of use to sensing purposes and otherwise.

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