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# Programmable All-Optical Talbot Amplifier Using XPM-Based Discrete Multilevel Time-Lens

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**Abstract:** We propose a programmable XPM-based Talbot amplifier where the gain factor is optically reconfigurable. The general equations of phase modulation and dispersion allow us to achieve different gain factors with a fixed dispersive medium. © 2022 The Author(s)

## 1. Introduction

The Talbot phenomenon has been exploited to implement noiseless intensity amplification of a pulse train based on an inverse temporal Talbot effect [1]. The amplifier configuration consists of an electro-optic phase modulator (EO-PM) followed by a dispersive medium. However, this method requires a change of the dispersive medium for each amplification gain factor, and hence a considerable change in the experimental setup. Additionally, a new programmable Talbot amplifier has been demonstrated to offer multiple amplification factors with a fixed dispersive element. This is accomplished by relying on the general equations of the applied temporal phases and the provided amount of dispersion [2]. The main drawback of this method is the EO-PM, which suffers from limited performance, such as the modulation bandwidth and the failure to produce complicated phase patterns in the case of high gain factors. Recently, a novel concept of an XPM-based time-lens (TL) has been proposed where the pump signal is shaped into discrete-multilevel (DM) in order to relax its power compared to other optical TL approaches [3]. Furthermore, this concept has been employed as a Talbot amplifier for noise mitigation but without the capability of tuning the gain factor with a fixed system due to the conventional equations [4].

In this work, we propose a programmable all-optical Talbot amplifier with an XPM-based discrete multilevel time-lens, in which the gain factor (from  $m = 2$  to 10) is optically reconfigurable by using a programmable optical pulse shaper (POPS). The reconfigurability of the system with a fixed dispersive medium is achieved by the general equations of phase modulation and dispersion.

## 2. Operation principle and results

Fig. 1 depicts the concept of the proposed programmable XPM-based Talbot amplifier. The main idea is to generate the pump signal  $P_{pump}(t)$  as a multilevel pulse train with a period of  $T_{pump} = m.T_r$  ( $T_r$  is the pulse rate of the probe signal  $P_{probe}(t)$ ) and a temporal width of  $\tau$  for each fundamental pulse  $x(t)$  of the pump, which is given by,

$$P_{pump}(t) = \frac{1}{2\gamma L} \sum_{n=-\infty}^{\infty} \varphi_n x(t - n\tau) \quad (1)$$

with  $\varphi_n$  are the temporal phases that must be applied on the  $n$ -th temporal pulse of the probe ( $n = 0, 1, 2, \dots$ ),  $\varphi_n = -(s/m)([1/s]_m)^2 \pi n^2$  if  $s.m$  is even ( $s$  is an integer and co-prime with  $m$  and  $[1/a]_b$  is the inverse of  $a$  modulo  $b$ ) and  $\varphi_n = -2(s/m)([1/2]_m)([1/2s]_m)^2 \pi(2n+m)^2$  if  $s.m$  is odd [2]. For both cases,  $\varphi_n$  are reduced to the  $[0, 2\pi]$  range, this allows us to obtain a periodic sequence of multilevel induced phases since  $\varphi_n$  are known to be periodic with a period given by the gain factor  $m$ .

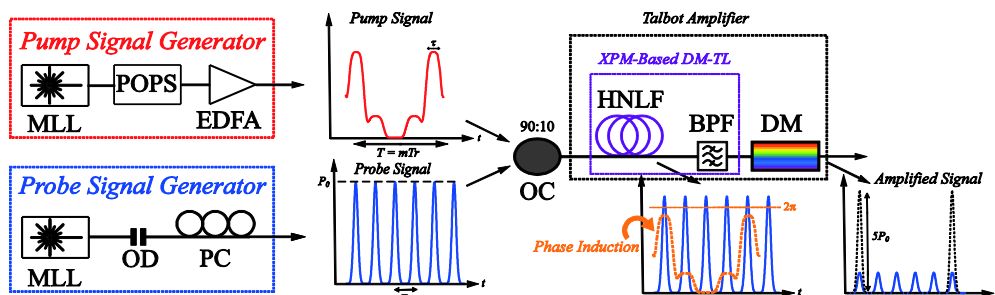


Fig. 1. General concept of the programmable all-optical Talbot amplifier with an XPM-based discrete multilevel time-lens. MLL: Mode-Locked Laser, EDFA: Erbium-Doped Fiber Amplifier, OD: Optical Delay, PC: Polarization Controller, OC: Optical Coupler, DM: Dispersive Medium, POPS: Programmable Optical Pulse Shaper, BPF: Bandpass Filter.

In Eq. (1),  $L$  is the effective length of the highly nonlinear optical fiber (HNLf) and  $\gamma$  is the nonlinear coefficient. The probe is synchronized with the pump by an optical delay and injected into the HNLf with a 90:10 coupler. When the probe and pump signals co-propagate through the nonlinear medium, the probe experiences a phase modulation of  $\phi_{NL}(t) = 2\gamma LP_{pump}(t)$ . After the HNLf, the pump is filtered-out by a bandpass filter. The probe is subsequently propagated through a dispersive medium that should provide an amount of dispersion of  $\psi_2 = (qm + m - s)mT_r^2 / 2\pi$ , with  $q = 0, 1, 2, \dots$  is a free design parameter [2]. By means of this general equation, we can target a maximum gain factor of  $M$  that fulfills the following condition:  $M = qm + m - s$ , with  $m \leq M$ . At this condition, we can acquire a number of amplification factors  $m$  less than or equal to  $M$  for a given  $s$  and  $q$ .

Now to validate our concept, we assume a probe pulse train with a repetition rate of 50 GHz ( $T_r = 20$  ps) at 1558 nm, each pulse has a Gaussian shape with a FWHM time duration of 5 ps. The fundamental pulse  $x(t)$  of the pump has a second-order super-Gaussian shape with a FWHM of  $\Delta t = k\tau = 0.7\tau$ , with  $\tau = 20$  ps. The use of shorter fundamental pulses of the pump leads to avoid interference and therefore a significant reduction of the power, which justifies the choice of  $k$ . The global pump (at 1544 nm) can easily be generated by a programmed all-optical pulse shaping technique for each specific period  $m.T_r$  [5]. We select a HNLf with  $\gamma = 25 \text{ W}^{-1}\text{km}^{-1}$ ,  $L = 1$  km, a dispersion slope of  $0.017 \text{ ps/nm}^2$  and a zero dispersion wavelength of  $\lambda_0 = 1551$  nm.

On the other hand, we have chosen  $M = 10$  in order to obtain gain factors of  $m = 2, 5$  and  $10$ , this corresponds to  $s = 1, 3$  and  $9$ , and  $q = 2, 0$  and  $0$ , respectively. According to these parameters, the fixed dispersive medium should provide a first-order dispersion coefficient of  $\psi_2 = 636.619 \text{ ps}^2/\text{rad}$  over the entire probe spectrum.

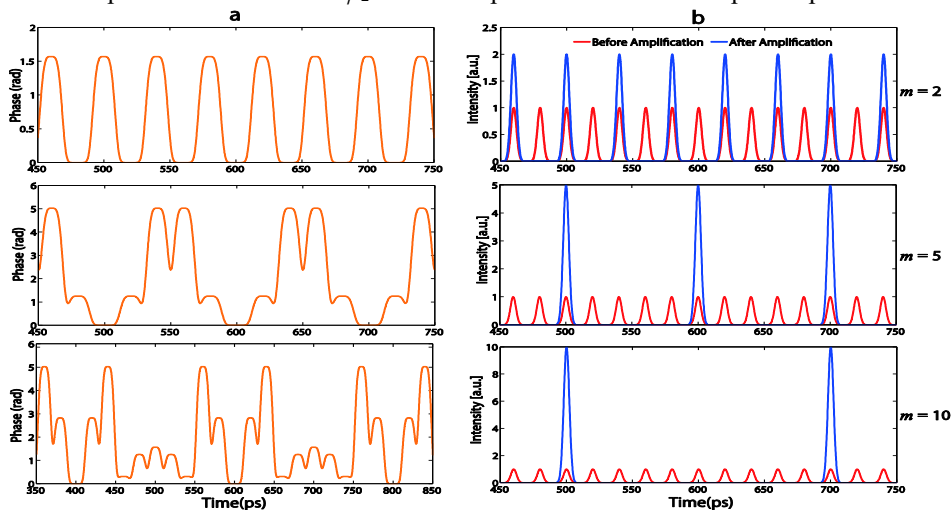


Fig. 2. Numerical results of the proposed Talbot amplifier. (a) The induced phases on the probe for each case of  $m$  (b) The probe pulse train before and after amplification for different gain factors.

Fig. 2 illustrates the obtained results that validate the proposed concept. Fig. 2(a) shows the applied phases profiles to the input probe pulse train for each case of  $m = 2, 5$  and  $10$  with periods of 40, 100 and 200 ps, respectively. The key element of this technique to get a high fidelity phases is the POPS in terms of the tunability of the temporal ranges, the finite spectral resolution of the shaper and the total optical bandwidth. Fig. 2(a) shows the normalized temporal intensity of the probe pulse train before and after amplification. As can be seen, even with high amplification factors, the output signal is an undistorted replica of the input signal with regard to the individual pulse properties (shape and duration) and without the pulse pedestal fluctuation shown in previous works [1,2].

In summary, we have presented a new concept of Talbot amplifier using XPM-based DM-TL and the general equations of phase modulation and dispersion. The results are in good agreement with the anticipated theory.

### 3. References

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