Abstract—In this paper, the propagation of optical pulses in Photonic Crystal Waveguides (PCWs), near the edge of the guided band is numerically investigated. In the linear regime, it is shown that group velocity dispersion can significantly limit the maximum bit rate of the optical signal. On the other hand, better performance is obtained using soliton waves. Both bright and dark solitons can significantly increase the maximum bit rate that can be achieved in the nanosecond delay regime. The influence of higher order dispersion and optical loss is numerically investigated. The results indicate that near the band-edge can be stable, soliton propagation in PCWs, provided that the optical losses are kept low. This could open a path towards implementing compact nonlinear elements and delay lines in integrated form.

Index Terms—

I. INTRODUCTION

Optics is the key for ultra broadband communications and optical fibers can presently carry information at Terabit per second data rates using Wavelength Division Multiplexing (WDM) [1]. Integrated optics may play an important role in the further development of optical technologies. Integrated components such as Arrayed Waveguide Grating (AWGs) multiplexers have already been commercialized [2]. Combined with Semiconductor Optical Amplifiers (SOAs) on a single chip, one can perform add/drop multiplexing of many wavelength channels [3]. However, the level of sophistication of integrated optical devices is still rather low, compared to electronics. The realization of multifunctional, higher density integrated optical devices is a key issue in order to implement various crucial optical signal processing functions on-chip. Nanophotonic technologies such as Photonic Crystals (PCs) [4] may eventually provide the means to achieve this goal. PCs are in essence periodic dielectric structures which, if properly designed, exhibit photonic bandgaps, i.e. range of frequencies where no propagating electromagnetic mode exists. By breaking the periodicity of the dielectric, one may realize many important optical components. Photonic Crystal Waveguides (PCWs) can be designed to guide light even through sharp waveguide bends [5], and this may significantly reduce the overall size of photonic chips. Figure 1, illustrates various examples of single mode periodic nanophotonic PCWs formed by introducing defects on an otherwise periodic rectangular or triangular bulk 2D PC of dielectric rods. Furthermore, many compact designs for optical filters [6],[7], and nonlinear processing elements [8] have also been proposed by introducing defects inside bulk PCs.

Figure 1: Examples of photonic crystal waveguides unit cells formed by a) removing a single rod from a square photonic lattice, b) inserting defect rods in a square lattice, c) removing a rod from a triangular lattice, d) inserting defect rods in a triangular lattice.

The ability to delay an optical signal is an important functionality in optical communication systems. Optical delay lines are needed in order to resolve the fundamental problem of contention in the case where multiple packets are destined for the same output port at the same time. The components are usually implemented using fiber loops, but these devices are bulky and do not offer a compact solution. On the other hand, relying on electronics to perform the buffering of optical packets, can cause heavy bottlenecks in high-speed optical networks. Slow light may constitute an alternative towards
realizing optical delay lines in integrated form. Slowing down the light also increases the strength of nonlinear phenomena which can be very useful in signal processing applications.

PCWs, which strongly exhibit this property near the band edge, and Coupled Resonator Optical Waveguides (CROWs) [9],[10] are some examples of slow light structures. Unfortunately, the propagation of signals in slow light devices is usually impaired by second and higher order dispersion [11],[12]. In the linear regime, dispersion causes pulse broadening and hence intersymbol interference, posing strict limits on the maximum bit rate that can be achieved at a specified delay. To exploit the low group velocity that these devices exhibit, one idea is to use soliton pulses as information carriers. Ideally, in a Kerr nonlinear lossless medium, where higher order (third order and above) dispersion is zero, the soliton pulse propagates without waveform distortion [13]. This is because the Kerr-induced, Self Phase Modulation (SPM) counteracts the effects of second order dispersion. This property was exploited in [14], where it was numerically shown that solitons may be used to achieve delays of the order of a few nanoseconds at 10Gb/s in CROWs. However, PC-based CROWs are still rather difficult to fabricate and it is interesting to investigate the delay achieved using soliton propagation in PCWs which are simpler to realize.

In this paper, the propagation of both linear and nonlinear pulses is numerically investigated in single mode 2D PCWs near the band edge (where the delay is increased). Both triangular and rectangular lattice waveguides are assumed such as the ones depicted in Figure 1. Calculations for 1cm long PCWs reveal that, for 1ns delay, linear pulses exhibit large broadenings for data rates just above 10Gb/s. On the other hand, using either bright or dark soliton pulses may lead to significant improvement provided that, the optical losses are kept low. Nonlinear pulse propagation near the band-edge, is investigated using the nonlinear propagation equation model derived in [15]. It is numerically shown that optical solitons may be used in order to achieve 1ns delay in 1cm long PCWs, at much higher data rates (40Gb/s and even 100Gb/s). Higher delays of the order of 5ns at 100Gb/s, can also be supported.

The rest of the paper is organized as follows: In section II, the model used for the study of both linear and nonlinear pulse propagation in PCWs is briefly reviewed. Using this model, the performance of optical PCW delay lines in the linear regime is analyzed in section III. In section IV the basic characteristics of optical solitons in PCWs are presented, while in section V, their performance is assessed in the presence of higher order dispersion and optical loss. Some concluding remarks are given in section V.

II. LINEAR AND NONLINEAR PULSE PROPAGATION IN PCWS

In this section, the propagation model for both linear and nonlinear optical signals inside a PCW, is briefly presented. The model is based on a propagation equation for the envelope $A(z,t)$ of the electric field (see [15] for the details of the derivation). It is an extension of the propagation equation derived for mono-mode constant cross-section waveguides [16], to the case of periodic cross section. Compared to other methods such as the nonlinear Finite Element Method [17], it provides a simple and accurate [15] picture of nonlinear dynamics in PCWs.

Assuming a narrow band signal around the frequency $\omega_0$, the electric field $E$ can be expressed in terms of the envelope function $A(z,t)$ [15]:

$$E(r,t) \cong A(z,t)e^{ik_zz-\omega_0t} + c.c.$$ (1)

In (1), $k_0$ and $\epsilon_0$ is the propagation constant and Bloch mode function at $\omega_0$ respectively. The dielectric constant, $\epsilon(r)$, of a Kerr nonlinear PCW, can be written as a sum of its linear part $\epsilon_0(r)$, and its nonlinear part which is proportional to the intensity $|E|^2$, i.e.

$$\epsilon(r) = \epsilon_0(r) + \epsilon_n(r)|E|^2$$ (2)

where

$$\epsilon_n(r) \equiv 2\epsilon_0n_0(r)(\epsilon_0(r)/\mu)^{1/2}$$ (3)

In (3), $\epsilon_0$ is the dielectric constant of vacuum, $n$ is the refractive index of the dielectric, $n_0(r)$ the nonlinear refractive index, and $\mu$ is the magnetic permeability. The propagation of optical pulses inside a PCW can be studied using the propagation equation [15]:

$$j\left(\frac{\partial A}{\partial z} + \frac{\Gamma}{2}A\right) + \sum_{l>2}^\infty j^{m(l)}\frac{A_lA}{l!}\frac{\partial^l A}{\partial t^l} + \gamma|A|^2A = 0$$ (4)

Equation (4) describes the pulse evolution $A(z,t)$ as it propagates along the PCW assuming a frame of reference $T=t-z/v_c$ moving with the group velocity $v_c$ of the signal. The coefficient $\Gamma$ is related to the optical losses which are caused either by disorder-induced scattering [18],[19] or by out-of-plane propagation losses [20]. The function $m(l)$ is defined by $m(l)=\text{mod}(l,2)$ while the coefficient $k_l$ is the group velocity dispersion coefficient (for $l=2$) or a higher order dispersion coefficient ($l>2$). These coefficients are calculated from the derivatives of the mode propagation constant $k$ with respect to the frequency $\omega$, i.e.

$$k_m = \frac{d^n k}{d\omega^n}_{\omega=\omega_0}$$ (5)

The group velocity $v_c$ is simply

$$v_c = (d\omega/dk)_{\omega=\omega_0} = 1/k_1$$ (6)

Around $\omega=\omega_0$, one can use the following Taylor expansion for the propagation constant:

$$k(\omega) = k(\omega_0) + \sum_{m=1}^\infty \frac{k_m}{m!}(\omega-\omega_0)^m$$ (7)

The coefficient $\gamma$ is the self phase modulation (SPM) coefficient and can be calculated using [15]:

$$\gamma = \frac{\epsilon_n}{\epsilon_0}$$
\[ \gamma = \frac{2\alpha}{a} \int \sqrt{dS_E_{NL}} |e_\gamma|^2 \]  

In (8) the constant \( a \) is the period of the lattice along the \( z \) direction and \( V \) is the volume of the unit cell of the waveguide. In linear waveguides, \( E_{NL}=0 \) and hence \( \gamma=0 \), in which case the propagation equation (4) is linear.

To calculate the coefficients \( k_u \), one can calculate the dispersion relation \( k=k(\omega) \) of the linear PCW (\( E_{NL}=0 \)) around the frequency \( \omega_0 \), using the Plane Wave Expansion (PWE) method [21]. The coefficients \( k_u \) can then be obtained, either by fitting the curve \( k=k(\omega) \) with a polynomial of \( \omega-\omega_0 \) (as indicated by (7)) or by using a finite difference approximation for the derivatives in (5). The PWE method can also be used to calculate the Bloch function of the electric field \( e_\gamma \) in the entire unit cell. Numerically integrating \( \sqrt{dS_E_{NL}} |e_\gamma|^2 \) over the entire unit cell, the value of \( \gamma \) is calculated. In the case of a 2D waveguide which is uniform along the \( y \) direction, the SPM coefficient \( \gamma_{2D} \) for the TM modes is written as [15]:

\[ \gamma_{2D} = \frac{2\alpha}{a} \int \sqrt{dS_E_{NL}} |e_\gamma|^2 \]  

where \( S_P \) is the area of the unit cell and \( e_\gamma \) is the \( \gamma \)-component Bloch function of the electric field. The results obtained for 2D structures can be approximately applied for 3D slab PCW structures, using effective index schemes [22]. One may obtain a first approximation of the SPM of a PC slab waveguide coefficient \( \gamma \) using \( \gamma_{2D}/\text{w}_{eff} \), where \( \text{w}_{eff} \) is the effective aperture of the guided mode along the \( y \) direction.

The above discussion reveals that, the coefficients of the propagation equation (4), can be calculated from the properties of the guided mode of the linear PCW. There are certain cases in which, equation (4) can be solved analytically. As in the case of linear optical fibers [23], in a linear PCW (\( \gamma=0 \)), it can be shown that an optical pulse having a Gaussian incident profile, \( d(0,T)=\exp(-T^2/2T_d^2) \), remains Gaussian in shape and is broadened by a factor of:

\[ B_{F1}(z) = \left(1 + \left(\frac{z}{L_D}\right)^2\right)^{1/2} \]  

where \( L_D \) is the dispersion length

\[ L_D = T_d^2 / \left|k_2\right| \]  

Equation (10) is derived in [23], ignoring higher order dispersion terms (\( k_f=0 \) for \( f>2 \)). Assuming a Return-to-Zero (RZ) modulation pulse, the pulse width \( T_0 \) can be chosen so that the Full Width at Half Maximum (FWHM), \( t_{FWHM} \), is equal to \( t_{FWHM} = 1/4R_c \). This will also be the choice for the FWHM of the soliton pulses examined in section V.

Equation (10) can be used in order to estimate the broadening due to group velocity dispersion in the linear regime and will form the basis for the calculations of the next section. Unfortunately, in the case of nonlinear propagation, equation (4) is much harder to solve analytically and one resorts in numerical techniques such as the Split Step Fourier (SSF) method [23]. This approach will be used in section IV, in order to study the nonlinear pulse propagation.

III. DELAY PERFORMANCE OF PCWS IN THE LINEAR REGIME

Figure 2(a) shows the dispersion curves of the guided modes for the waveguides of Figure 1, calculated using PWE. The rods have a refractive index equal to \( n_p=3.5 \) and are surrounded by a background material with \( n_s=1.5 \). The lattice rods radii are \( r_a=0.25a \), and the lattice constant \( a \) is chosen so that the bandgap center is at \( \lambda=1.55\mu m \). For the waveguides of Figure 1(b) and (d), the central defect rod had a radius equal to \( r_d=0.175a \). In Figure 2(a) the dispersion relation \( \omega=\omega(k) \) of the guided modes is plotted inside the photonic bandgap. Outside the bandgap, there is no propagating mode confined near the defect. 19 plane waves were used in the \( z \)-direction and 59 in the \( x \)-direction. To estimate the group velocity \( v_g \) of the pulse, one can use a simple finite difference approximation for the derivative in (6). The slow down factor \( S_c=e^{-v_g/T_0} \), where \( c \) is the speed of light in vacuum, obtained for the waveguide structures of Figure 1 is plotted in Figure 2(b). There is a large increase in \( S \), at wavelengths near the two band-edges of the guided mode. It is interesting to note that defect type waveguides, with \( r_d=0.175a \) achieve higher slow down factors than hollow type waveguides (\( r_d=0 \)) of the same lattice type. In addition, triangular lattices achieve higher slow down factors than rectangular lattices for the same \( r_a \).

Given the length \( L \) of the PCW waveguide, one can calculate the delay \( T_{delay}(\lambda)=LSc \) as a function of the wavelength \( \lambda \). Once the specified delay value, \( T_d \), is determined, the central wavelength \( \lambda_0 \) of the optical signal is calculated, numerically solving the equation \( T_{delay}(\lambda_0)=T_d \). As indicated by Figure 2(b), there can be two wavelengths \( \lambda_01 \) and \( \lambda_02 \) for which the delay attains a specific value \( T_d \). If \( T_d \) is high enough, these values will be close to the left and right band edge corresponding to \( k_0=0 \) and large \( k \) respectively. In Figure 3(a)-(b) the \( y \) electric field component is shown, for the rectangular lattice, defect-type waveguides near the left and right band edge respectively, assuming \( T_d=1ns \). It can be seen that both fields decay away from the defect rod. Especially, at the right band edge (large value of \( k \)), the field is strongly localized near the defect rod. Similar conclusions are drawn for the modes of triangular lattice waveguides which are shown in Figure 3(c)-(d) for the left and right band edge respectively, assuming \( T_d=1ns \).

In any case the large decrease in \( v_g \) near the band edge, usually comes at the expense of a large second order dispersion coefficient \( k_2 \), which can significantly broaden the propagating pulse in the linear regime according to (10)-(11). The waveguide design influences the value of \( k_2 \) and has a bearing on the delay line performance. Varying the value of \( r_a \), one can obtain different values for \( k_2 \) at the frequency launch point. This is shown in Figure 4, where the value of \( k_2 \) corresponding to \( T_d=1ns \) for \( L=1cm \) long triangular waveguides is plotted. As \( r_a \) approaches \( r_d \), \( k_2 \) is reduced. However, in practical situations, the value of \( k_2 \) is not the only factor determining the choice of waveguide design. Especially in nanophotonic applications, transverse mode confinement is
also an important parameter. Although in designs where \( r_d \) is closer to \( r_m=0.25a \), than \( r_m=0.175a \), one may achieve slightly smaller \( k_2 \), mode confinement gets much poorer near the left band-edge. This is why such designs are not considered in this study. It should also be noted that as \( r_d \) exceeds \( r_m \), the PCW eventually becomes two-mode and this is why values of \( r_d \) larger than \( r_m \) are not included in Figure 4.

Once the value of \( k_2 \) is determined, the broadening factor can be estimated using (10). In Figure 5(a) and (b), this factor is plotted for the four PCWs in question, assuming \( T_{D}=1 \text{ns} \) and 5ns respectively, and 1cm long waveguides. The launch point is taken near the left band edge where the values of \( k_2 \) are smaller (see Figure 4). It is deduced that for \( R_b \approx 10 \text{Gb/s} \) and \( T_{D}=1 \text{ns} \), \( BF_2 \) is lower than 1.33 (corresponding to the limit for dispersion-induced broadening [5]) only in the case of the defect-type triangular lattice PCW. This PCW can support 12Gb/s signal at this limit. For \( T_{D}=5 \text{ns} \), the broadening factors are prohibitive, even for data rates slightly above 1Gb/s.

A similar behavior is observed when the launch wavelength corresponds to the right band of the guided band as seen in Figure 6. For \( T_{D}=1 \text{ns} \), the triangular lattice, defect-type, PCW is again the best design, supporting up to 11Gb/s data rates at the 33% broadening limit. For the rest of the structures, the maximum bit rates that can be supported are even less, while the broadening factors are again prohibitive for \( T_{D}=5 \text{ns} \). These results indicate that, the data rates that can be supported in linear PCWs are limited due to the dispersion-induced broadening, especially in the case where large delays are required.

IV. CHARACTERISTICS OF OPTICAL SOLITONS IN PCWS

As explained in the introduction, optical soliton pulses may experience less dispersion-induced broadening than linear pulses. In the ideal case, where all higher-order dispersion terms are zero in (4) \( k_2=0 \), for \( z \geq 3 \), and optical losses are also neglected \( (v=0) \), soliton waves propagate undistorted in shape. The shape of the soliton wave, differs according to the sign of the group velocity coefficient \( k_2 \). When \( k_2<0 \), pulse-like solitons are supported, usually referred to as bright solitons, while when \( k_2>0 \), dark solitons are supported, exhibiting a dip in a uniform bright background. For the PCWs of Figure 1, the dispersion relation is such that \( k_2<0 \) and \( k_2>0 \) near the left and right band edge respectively, so both types of solitons can be considered.

The evolution of bright solitons is determined by:

\[
A(z, T) = \sqrt{P_0} \text{sech} \left( \frac{T}{T_0} \right) \exp \left( j \frac{z}{2L_D} \right) \tag{12}
\]

As seen by (12), there is no pulse broadening due to \( k_2 \) since \( |A(z, T)| \) is not a function of \( z \). In (12), \( T_0 \) is the initial soliton width determined by \( T_0 \approx t_{FWHM}/1.76 \), where \( t_{FWHM} \) is the full-width half-maximum of the pulse, \( L_D = T_0^2/|k_2| \) is the dispersion length, \( P_0 \) is the soliton peak power, determined by

\[
P_0 = \frac{|k_2|^2}{\gamma T_0^3} \tag{13}
\]

To calculate the required soliton peak power, one can use and equation (13) and the fact that \( t_{FWHM}^r = 1/4R_b \) and \( R_b \approx t_{FWHM}^r \approx 1.76 \). The following equation is obtained relating the peak power and the bit rate \( R_b \):

\[
P_\text{b} \approx 49.5 \frac{|k_2|^2}{\gamma} R_b^2 \tag{14}
\]

In Figure 7, the relation between the peak power of the soliton and the bit rate is plotted for hollow and defect-type waveguides formed either on a rectangular or a triangular PC lattice. The defect-type waveguides have a defect rod radius \( r_m=0.175a \). For a given \( R_b \), the choice of waveguide significantly affects the required soliton peak power. For 2D structures, setting \( \gamma = 2D \) yields the power density along the vertical direction (\( \gamma \) direction) measured in W/m. To obtain an estimate on the power required, one must multiply the power density with the effective mode aperture \( w_{eff} \) along the vertical direction. Table I shows the related values of the dark soliton peak power in mW assuming an effective aperture \( w_{eff} = 0.5 \text{m} \) for \( R_b = 10 \text{Gb/s} \). For all calculations the nonlinear refractive index was taken \( n_2 = 1.5 \times 10^{-16} \text{m}^2/\text{W} \). It can be deduced that the power required to launch soliton pulses inside a PCW is not excessive. In addition, the choice of lattice design can reduce power requirements; triangular lattices require significantly less power than rectangular lattices.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SOLITON PEAK POWER FOR VARIOUS TYPES OF PHOTONIC CRYSTAL WAVEGUIDES FOR A BIT RATE OF 10GB/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Type</td>
<td>Rectangular Lattice</td>
</tr>
<tr>
<td>( r_d )</td>
<td>Peak Power (mW)</td>
</tr>
<tr>
<td>0</td>
<td>89</td>
</tr>
<tr>
<td>0.175a</td>
<td>37</td>
</tr>
</tbody>
</table>

To prevent soliton collisions, one must carefully choose the soliton pulse width \( t_{FWHM} \). In this paper, we have chosen \( t_{FWHM} = 1/4R_b \) as in the case of linear pulses in order to limit soliton collision [23]. One could alternatively choose a larger value for \( t_{FWHM} \) and launch consecutive solitons with a relative phase difference to prevent collisions [23].

Dark soliton evolution is governed by:

\[
A(z, T) = \sqrt{P_0} \text{tanh} \left( \frac{T}{T_0} \right) \exp \left( j \frac{z}{L_D} \right) \tag{15}
\]

Actually, the only difference between the dark and bright soliton in equations (12) and (15) is the sech and tanh time dependence respectively. This is illustrated in Figure 8 which presents the initial shape of bright and dark solitons at \( z=0 \).

To investigate the influence of higher order dispersion and optical loss in the stability of the soliton, one may numerically solve the propagation equation using the SSF method setting the suitable initial condition for bright and dark solitons.
respectively. For bright solitons one simply uses 
\[ A(0,T) = P_0 \frac{1}{\sqrt{T}} \text{sech}(T/T_0) \] 
as an initial conditions. On the other hand, dark solitons also require a bright background which can be considered as a broad Gaussian pulse with FWHM ten times that of the soliton dip [24].

Instead of using (10), the broadening factor \( BF_{NL} \) at the nonlinear regime, is numerically calculated as:

\[ BF_{NL}(L) = \frac{B_{\text{sat}}(L)}{B_{\text{sat}}(0)} \tag{16} \]

where \( B_{\text{sat}} \) is the numerically computed full width at half maximum of the envelope pulse \( A(L,T) \). This approach will be used in the next section, to investigate the robustness of optical solitons in the presence of higher order dispersion effects and optical loss.

V. SOLITON PROPAGATION IN PCWS.

In this section, the robustness of optical soliton pulses against the influence of higher order dispersion effects and attenuation will be numerically investigated.

A. Higher order dispersion Effects

The influence of higher order dispersion can broaden the soliton pulse and undermine the performance of the delay line. The values of the broadening factor \( BF_{NL} \) of a bright soliton, with respect to the bit rate for the PCWs of Figure 1, are plotted in Figure 9(a) and (b) for \( T_{\text{r}}=1\text{ns} \) and \( T_{\text{r}}=5\text{ns} \) respectively. The PCW length was set to 1cm and optical losses were neglected. It is interesting to note that the broadening factor is much smaller than 1.1, implying a broadening of less than 10% for bit rates of up to 100Gb/s at 1ns delay. The broadening factors obtained are generally much larger for dark solitons. For \( T_{\text{r}}=5\text{ns} \), higher order dispersion has a greater degrading effect, limiting the bit rate to maximum value of 10Gb/s. However, compared to the linear case Figure 5(b), this is still a significant improvement.

Higher order dispersion can also displace the soliton pulse, effectively changing the value of \( r_k \). This means that the actual delay \( T_{\text{del}} \) achieved can be somewhat smaller than \( T_d \) by an amount \( \Delta T = T_d - T_{\text{del}} \). To measure the values of \( \Delta T \), one can estimate the temporal displacement of \( A(z,T) \) along the \( T \)-axis. In Figure 10(a) and (b), the values of \( \Delta T \) at 10Gb/s are plotted for \( T_{\text{r}}=1\text{ns} \) and \( T_{\text{r}}=5\text{ns} \) respectively. It is deduced that \( \Delta T \) is very small for \( T_{\text{r}}=1\text{ns} \), though somewhat larger for \( T_{\text{r}}=5\text{ns} \). For the triangular lattice PCWs with \( r_k=0.175a \), \( \Delta T \) is approximately 0.11ns at \( T_{\text{r}}=5\text{ns} \) and \( B_{\text{sat}}=10\text{Gb/s} \), implying that the achieved delay is actually \( T_{\text{del}}=4.89\text{ns} \).

It is also interesting to assess the influence of higher order dispersion in the propagation of dark solitons. Near the right side of the band edge where \( k_z=0 \), one obtains different values of the higher order dispersion coefficients \( k_z \) (\( l=2 \)), so the performance of the delay line will also differ. The broadening factor can again be estimated numerically using equation (16), except that in this case, one measures the 3dB bandwidth of the dark soliton dip. The results are presented in Figure 11(a) and (b) for 1ns and 5ns delay respectively. The waveguide length is again \( L=1\text{cm} \). It is shown that for 1ns delay, the defect-type, triangular lattice PCW can support bit rates up to 100Gb/s without significant broadening, while the rectangular, defect type PCW can support up to 70Gb/s before the pulses reach the 33% broadening limit. For a delay of 5ns, dark solitons can support transmission rates of 10Gb/s for the defect type triangular PCW. For the other PCWs of Figure 1, the bitrates that could be supported were significantly lower and are not included in Figure 11(b). Compared to the linear case, dark solitons also provide significant performance improvement, but they are less effective than bright solitons.

However, as indicated in Figure 3, the optical field is better confined near the right band-edge where dark soliton are supported. This means that dark solitons maybe more suitable information carriers in nanophotonic applications where the mode field confinement is an important issue.

B. Influence of Optical Loss

Since optical solitons propagate undistorted only when no waveguide is lossless, it is interesting to consider the impact of optical attenuation. Figure 12(a) depicts the values of the broadening factor for various values of the optical loss coefficient \( \Gamma \) in a defect-type PCW with \( r_k=0.175a \), obtained for a 10Gb/s bright soliton signal, at a specified delay of \( T_{\text{r}}=1\text{ns} \). It is seen that even for losses of up to 1dB/mm, the optical pulse does not broaden significantly. However, as the data rate is increased, the influence of optical loss becomes much more critical. Figure 12(b) shows the broadening factor obtained for a bright soliton signal of 100Gb/s for the same waveguide structure. It is deduced that the optical loss must now be kept smaller than 0.1dB/mm in order to avoid pulse broadening beyond 30%. These considerations demonstrate the importance of reducing the optical losses and towards this end, various distributed amplification schemes can be used such as Raman amplification [25] or quantum wells [26][27]. Efficient PC slab designs can also lead to optical loss reduction [28].

VI. CONCLUSIONS

In this paper, the possibility of achieving nanosecond order delays, near the band edges of 2D photonic crystal waveguides was numerically investigated. Linear pulse propagation was shown to be severely impaired by second order dispersion. In the nonlinear regime, both bright and dark optical soliton pulses can be used to provide nanosecond delays for optical signals up to 100Gb/s. Third and higher order dispersion was shown not to significantly affect the performance of the soliton delay line. The influence of optical loss was also investigated and it was numerically shown that high bit rate soliton signals require low loss in order to limit their broadening factor. The results of this paper indicate that soliton propagation in photonic crystal waveguides may open a path towards achieving future compact optical delay lines and nonlinear elements in integrated form.

REFERENCES

Figure 2: a) Dispersion relations and b) Slow down factors for the guided mode of PCWs depicted in Figure 1.

Figure 3: Normalized field intensity of guided modes for 2D PCWs, with defect rod radius $r_d$.

Figure 4: Values of $k^2$ obtained for a triangular lattice PCW with defect rod radius $r_d$ when $T_d=1\text{ns}$.

Figure 5: Linear Broadening factor for hollow and defect-type PCW waveguide formed in either rectangular or triangular PC lattice at the left band edge when a) $T_d=1\text{ns}$ and b) $T_d=5\text{ns}$.
Figure 6: Linear Broadening factor for hollow and defect-type PCW waveguide formed in either rectangular or triangular PC lattice at the right band-edge when a) $T_d=1\text{ns}$ and b) $T_d=5\text{ns}$.

Figure 7: Relation between the required soliton peak power density $P_0$ and the bit rate $R_b$ for delay $T_d=1\text{ns}$.

Figure 8: Normalized envelope initial $A(0,T)$ for bright and dark soliton pulses.

Figure 9: Broadening factors for bright solitons propagation in various geometries of PCWs obtained at a specified delay of either a) $T_d=1\text{ns}$ for signals up to 100Gb/s and b) $T_d=5\text{ns}$ for signals up to 10Gb/s.

Figure 10: Values of the temporal pulse displacement $\Delta T$ caused by higher order dispersion for the types of PCWs in Figure 1 obtained at specified delays $T_d$ equal to a) 1ns and b) 5ns.
Figure 11: Broadening factors for dark soliton propagation in various geometries of PCWs obtained at a specified delay of either a) $T_d=1\text{ns}$ for signals up to $100\text{Gb/s}$ and b) $T_d=5\text{ns}$ for signals up to $20\text{Gb/s}$.

Figure 12: Broadening factor as a function of waveguide attenuation $\Gamma(\text{dB/mm})$ for a signal of a) $10\text{Gb/s}$ and b) $100\text{Gb/s}$, at $T_d=1\text{ns}$. 