Cryan, M. J., Cao, T., Ivanov, P., Craddock, I. J., Rorison, J. M., Yu, S., ... Karle, T. J. (2006). Electromagnetic modelling of a monolithic pulse reshaper based on a photonic crystal waveguide integrated with a SOA. In International Conference on Transparent Optical Networks, Nottingham, UK. (Vol. 2, pp. 19 - 22). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/ICTON.2006.248312

Electromagnetic Modelling of a Monolithic Pulse Reshaper based on a Photonic Crystal Waveguide Integrated with a SOA

M.J. Cryan, T. Cao, P.S. Ivanov, I.J. Craddock, S. Yu, J. Rorison and C.J. Railton
Centre for Communications Research, Department of Electronic and Electrical Engineering
University of Bristol, Bristol, BS8 1UB, UK, email: m.cryan@bristol.ac.uk
J.-Z. Zhang and I. Galbraith
Physics, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
T.J. Karle
School of Physics and Astronomy, University of St.Andrews, St. Andrews, Fife, KY16 9SS, Scotland, UK

ABSTRACT

Finite Difference Time Domain (FDTD) and Finite Element (FE) frequency domain methods are used to study the propagation of arbitrary chirped pulses in Photonic Crystal (PhC) waveguide. An arbitrary chirped pulse is derived from a separate Semiconductor Optical Amplifier (SOA) model and is passed through a mini-stop band (MSB) in a Photonic crystal waveguide. Good agreement is shown between the FDTD and FE models and pulse compression is observed.

1. INTRODUCTION

Photonic crystal waveguides (PhC-WGs) show strong confinement and dispersion behaviour and only recently have attempts been made to exploit the latter of these effects [1, 2]. One application of interest is pulse compression, this is well understood and widely used in fibre based systems [3] and has recently been demonstrated in a coupled cavity PhC waveguide system [2]. It is well known that PhC-WGs possess mini-stopbands due to mode coupling caused by the periodicity of the waveguide wall [4]. Near to a MSB it is also known that dispersion will be quite strong[5, 6], thus it might be anticipated that pulse compression effects could be obtained. Previously a PhC-WG has been designed, for filtering applications, to have a large MSB near 1550 nm [7], thus it is an ideal system to investigate pulse compression effects.

This paper presents results using both the FDTD method and the frequency domain FE method. We present an arbitrary chirped pulse(ACP) propagating through W3 modified PhC waveguide. In this case, a Finite Difference Time Domain (FDTD) method is developed where pulse data can be read in from a data file. This has allowed the FDTD code to be used in combination with a semiconductor optical amplifier model to study sub-picosecond pulses. In [8] it has been shown how time domain data from a semiconductor optical amplifier model can be read directly into a FDTD model in order to study the propagation of pulses with complex non-linear chirp. Here, we use the FE method to validate these results in terms of transmission response and time domain behaviour. The time domain response is analysed by determining the magnitude and phase response of the PhC waveguide together with the use of Fourier Transforms. It is felt that working with fullwave numerical methods such as FDTD and FE enables the complex dispersion found in finite length PhC waveguides to be studied in detail. In particular no approximations regarding the parabolic nature of the dispersion relation and infinite length are used and this ensures that all higher order dispersion terms are included in the analysis.

The FDTD results in this paper can take many hours to compute and this is a major disadvantage of many time domain methods. However in terms of time-per-frequency point after the use of Fourier transforms the approach is competitive with frequency domain methods. Most of the results in this paper are computed using a dedicated 160 machine Pentium 4 cluster, dynamically expandable to 260 machines when idle departmental machines are included. This uses the condor system [10] and allows multiple simultaneous simulations to be run, dramatically reducing overall run time for the results in the paper. It should also be pointed out that parallel FDTD, which is available commercially, would allow these types of problems to be run in a fraction of the time and the advent of low cost 64Bit computing will remove RAM limitations from which many numerical methods can suffer.

2. TIME DOMAIN MODELLING

In order to study pulse compression in the time domain it is necessary to be able to model chirped pulses [3]. A chirped pulse is one where the carrier frequency of the pulse changes with time. The simplest case of this is known as linear chirp where the frequency changes linearly across the pulse. Equation 1 below shows the expression for the electric field amplitude of a linearly chirped pulse in the time domain [3]

$$E(t) = \exp\left(-\frac{1}{2}\frac{(t-d)^2}{t_o^2}\right)\cos\left(\omega_o t - \left(\frac{1}{2}C\frac{(t-d)^2}{t_o^2}\right)\right). \tag{1}$$

1-4244-0236-0/06/$20.00 ©2006 IEEE

Where, d is the time delay of the centre of the pulse, ω_0 is the radial carrier frequency, t_0 is the half-width at 1/e intensity, and C is the chirp parameter. The expression shows that we have a Gaussian shaped amplitude term multiplied by a carrier wave whose frequency varies with time. We can understand what the C parameter means physically by differentiating the phase term in equation 1.

$$\frac{d\phi}{dt} = \omega_o - \left(C\frac{(t-d)}{t_o^2} \right). \tag{2}$$

Equation 2 shows how the radial frequency is changing across the pulse and the linear relationship between time and frequency is clear. If we now differentiate again we obtain

$$\frac{d^2\phi}{dt^2} = \frac{d\omega}{dt} = -\frac{C}{t_o^2}. \tag{3}$$

Equation 3 shows that C is the rate of change of radial frequency across the pulse scaled by the square of the half-width at 1/e intensity. The C parameter can then be used in combination with the dispersion relation for the particular waveguide [3] to describe pulse dispersion. The dispersion relation is described in terms of ω-β diagrams, where β is the propagation constant. From these diagrams we can calculate the Group Velocity Dispersion (GVD), this is the second derivative of β with respect to ω, known as β_2. It can be shown that that for pulse compression to occur the following relation must hold.

$$\beta_2 C < 0. \tag{4}$$

Thus β_2 and C must have opposite signs for compression to occur. However, an important point must be stressed here, this assumption is only true when the higher order derivatives of the dispersion relation are assumed to be zero i.e $\beta_3 = \beta_4 = \ldots = 0$. For fibre based systems, with typical pulse widths greater than a few 10's of picoseconds, this is a reasonable assumption, however in the strong dispersion environment of PhC guides, this may not be true and much more complex pulse behaviour can occur as outlined in [3]. This paper concentrates on ultrashort pulses with pulses widths in the order of picoseconds, this too increases the importance of higher order dispersion terms [3]. Thus having implemented the chirped pulse excitation in FDTD it will be possible to study the interaction of chirped pulses with the complex dispersion relations of finite length PhC waveguides in a very direct way. This approach is seen as complimentary to a purely frequency domain – dispersion relation approach. Thus Equation 1 has been implemented in an in-house FDTD code and it has been used to study the propagation of chirped pulses in PhC waveguides, in particular here we will study the propagation of pulses whose carrier wavelengths are near to a MSB.

3. RESULTS AND DISCUSSION

Figure 1 shows a top view of the structure to be studied. This is a narrowed W3 waveguide in the Γ-K direction. The waveguide is excited by a simple top-hat distribution placed across the photonic wire input waveguide. This paper deals only with TE mode excitation, that is E_x is the dominant field component and the E field is restricted to be in the plane of the page. The small circles in figure 1 represent monitors for all 3 field components in the time domain and this enables the intensity to be calculated at the output of the waveguide in both time and frequency domains. The transmission response of the structure is calculated by first performing a simulation with a simple straight waveguide and no PhC present and monitoring 10 field points across the input of the waveguide.

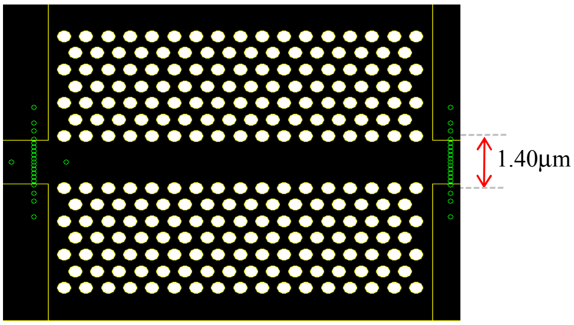

Fig. 1. FDTD model of a narrowed W3 PhC waveguide with a = 480 nm, r/a=0.329, Γ-K direction, n = 3.24, length =10 µm, FDTD mesh size in horizontal and vertical direction = 10 nm.

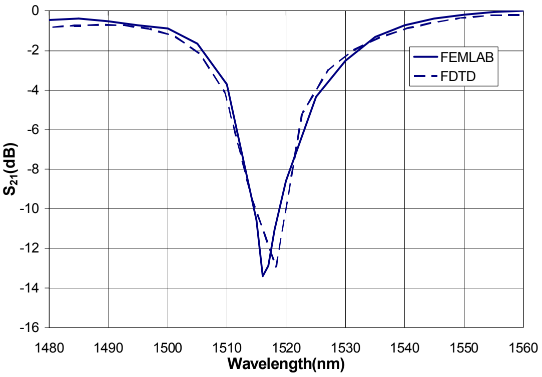

Figure 2. FDTD and FEMLAB simulated transmission for PhC waveguide of figure 1.

Figure 2 shows a comparison between FDTD and a commercial frequency domain Finite Element method based code (FEMLAB) for the transmission through structure of figure 1. It can be seen that good agreement has been obtained.

3.1 Arbitrary Chirped Pulse

The ACP-FDTD code enables pulses derived from other device models to be input into a FDTD simulation. A SOA model has been chosen since this then describes an integrated pulse reshaper, which would be of great interest. A comprehensive quantum well SOA model has been used which accounts for both spectral hole burning and carrier heating [9]. Propagation through the SOA is modelled using the Slowly Varying Envelope Approximation which is coupled to the polarization equations via the polarization source term. This results in very realistic output pulses and enables detailed design of a pulse reshaper to be undertaken.

The SOA that has been modelled is 500 μm in length and has an input pulse width of 150 fs (FWHM), centred at 1518 nm. The output pulse is then fed into a PhC waveguide described in figure 1. Figure 3 shows the input and output pulses (w.r.t the PhC waveguide) for the case of 60 MW/cm^2 input power to the SOA. Pulse compression can be clearly observed and has been calculated to be 3.25:1. It can also be seen that the pulse amplitude is decreased by the MSB, but overall for the SOA/PhC waveguide, amplification is being maintained. Figure 3 also shows the case where the pulse centre wavelength is moved further from the MSB to 1550 nm and the pulse is now being dispersed.

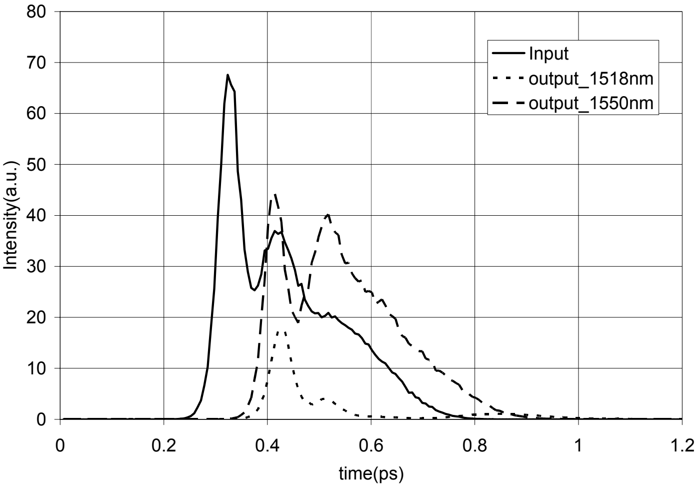

Fig. 3. Input and output pulse from PhC waveguide, centre wavelength = 1518 nm and 1550 nm, input pulse peak intensity is 60 MW/cm^2.

We have developed a time domain model using the frequency domain FEMLAB in order to validate the FDTD results. The time domain response is analysed by determining the magnitude and phase response of the PhC waveguide together with the use of Fourier Transforms. The results for this method are shown in figure 4 and figure 5 respectively. They show that a good agreement of the output pulse of the PhC waveguide is being obtained between FDTD and FEMLAB when the carrier wavelength of the pulse is at 1518 nm and 1550 nm.

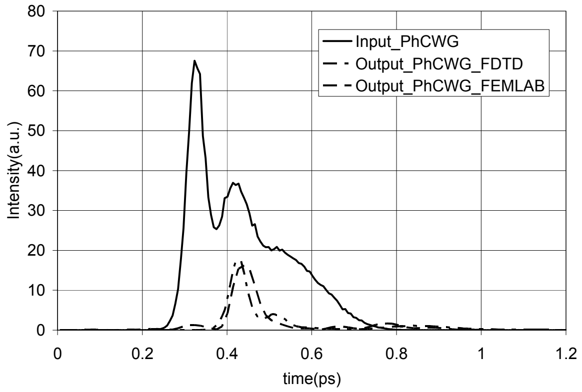

Fig. 4. Comparison of FDTD and FEMLAB output pulse in time domain, centre wavelength =1518 nm.

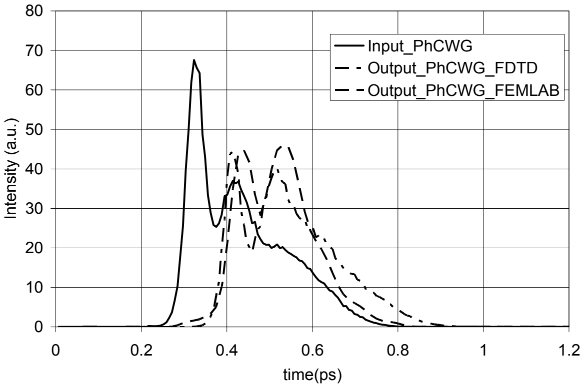

Fig. 5. Comparison of FDTD and FEMLAB output pulse in time domain, centre wavelength =1550 nm.

4. CONCLUSIONS

This paper has presented 2D-FDTD modelling and 2D FE modelling relating to the propagation of a non-linear chirped pulse propagating through a MSB and found very good agreement. The FDTD code was used to model the transmission of a non-linearly chirped pulse derived from a SOA model and pulse compression is observed. The frequency domain FE method has been used to validate these results and to show alternative routes to time domain modelling. This work has shown encouraging results for a pulse reshaper using PhCs and with further optimisation of the MSB transmission response improved pulse reshaping is anticipated.

ACKNOWLEDGEMENTS

This work is funded by the Ultrafast Photonics Collaboration (UPC), UK. (www.ultrafast-photonics.org).

REFERENCES

[1] M. Notomi *et al.*: Extremely Large Group-Velocity Dispersion of Line-Defect Waveguides in Photonic Crystal Slabs, *Phys. Rev. Lett.*, vol. 87, no. 25, Dec. 2001.

[2] T. J. Karle *et al.*: Observation of Pulse Compression in Photonic Crystal Coupled Cavity Waveguides, IEEE Journal Of Lightwave Technology, vol. 22, no. 2, February 2004.

[3] G.P. Agrawal, Fiber-optic communication systems, Wiley, 1992.

[4] S.Olivier *et al.*: Mini-stopbands of a one-dimensional system: The channel waveguide in a two-dimensional photonic crystal, *Phys Rev. B*, vol. 63, p.11331, Mar. 2001.

[5] A. Xing *et al.*: Pulse compression in Line Defect Photonic Waveguide, *in Proceedings of the Optical Fiber Communications Conference 2005, Paper OWD5.*

[6] M. Davanço *et al* : Detailed characterization of slow and dispersive propagation near a mini-stop-band of an InP photonic crystal waveguide *Optics Express* , vol. 13, no. 13, 27 June 2005.

[7] M.Cryan *et al.*: Design and Simulation of a Photonic Crystal Waveguide Filter Using the FDTD Method, *IEEE LEOS, Glasgow*, Nov. 2002.

[8] T. Cao *et al* : Modelling of a 2D Photonic Crystal Waveguide Pulse Reshaper Integrated with a SOA, *CLEO Europe, Munich, Germany*, June 2005.

[9] J.-Z. Zhang *et al.*: Rabi oscillations of ultrashort optical pulses in 1.55 um InGaAs/InGaAsP quantum-well amplifiers, *Journal of Applied Physics*, vol. 96, no. 1, 1st July 2004.

[10] *http://www.cs.wisc.edu/condor/*