Formation of Discrete Pulses using Taper Defects in Photonic Crystals

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Abstract

A two-dimensional photonic crystal based on a lattice of silicon rods in air with a photonic bandgap in the visible and near-ultraviolet spectra is proposed, by removing some of the silicon rods or resizing their radius, to create a monotonically varying tapered line defect, thereby pertaining to a case of structure-based nonlinearity and making it possible to operate with low input powers. By properly manipulating the length of the line defect, pulse compression and consequent adiabatic amplification is seen, along with bunching/anti-bunching of pulses. For certain modes of operation, field confinement is observed, and this leads to the formation of discrete pulses, or light bullets. Following this, by appropriate use of cavity defects, the localization of discrete pulses is obtained, with the 'gate'-output transfer curve resembling optical bistability. Such a structure can be used as a multi-functional device, with some of the functionalities being optical non-pumped amplification, frequency upconversion, memory writing, matched termination and slow wave guiding, that form the major conclusions of the work.

Keywords: Two-dimensional photonic crystal, tapering of defect, pulse compression, light bullets, optical amplification, optical attenuation, slow wave guiding

1. Introduction

Nano-optic technology encompasses a plethora of all-optical applications such as switching, amplification, memory storage, attenuation, etc. Among the various nano-optical devices that exhibit the above mentioned applications, photonic crystals stand at the forefront due to their versatile nature [1, 2, 3, 4, 5].

Various types of photonic crystals have been reported, which have been broadly categorized into one, two and three dimensional photonic crystals [6]. Examples of one-dimensional photonic crystals are fiber Bragg gratings [5]. Two-dimensional photonic crystals, examples of which include photonic crystal fibers and planar photonic crystal waveguides have been extensively reported in literature, with applications ranging from telecommunications to biosensing [7, 8, 9, 10, 11]. Three-dimensional photonic crystals include woodpile-based structures, and have been reported in [12, 13].

Extensive research has been conducted with regard to the effective manipulation of photonic crystal lattice defects for efficient all-optical signal processing applications[6, 8, 9, 10, 13, 14, 15], most notable among them being the design of photonic crystal based slow-wave structures [16, 17]. Extensive research work has been done in the domain of dispersion management and slow-wave guiding using material based nonlinearity as in [16, 18]. The immediate consequence of such waveguides is field confinement[12]. Such confinements result in optical light bullets, as have been reported in [7], and light bullets find applications in spatial multipliers and memory elements[19].

Once field confinement is achieved, one can observe spatial localizations of pulses. These spatial localizations result in pulse compression, and hence adiabatically, amplification is also made possible. By reversing the input and output positions, the exact complementary action, attenuation can be observed. Also, for certain modes of operation one observes bunching and anti-bunching of pulses, similar to ones reported in [20], and such phenomena finds potential applications in all-optical dense memory designs. On the other hand, when there is no field confinement, optical light bullets cannot be observed. But still, one can achieve adiabatic amplification without the use of an external pump. This may find applications in all-optical biosensors[21] and other such instrumentation amplifiers.

The present paper purports to the designing of photonic crystals with tapering of the lattice defects, such that the above mentioned applications can be achieved using simple defect arrangements, operating in the visible region of the electromagnetic spectrum. Such a structure can be used as a multi-functional optical component, with some of the observed functionalities being amplification, matched termination and memory writing devices, which form the major emphases of the work.

2. Design of taper defect

The band-gap diagram, a dispersion relation between angular frequency ω and the wave vector k, is as shown in Fig.(1). One observes a significant band-gap between band-1 (corresponding to $\frac{a}{\lambda}$ of 0-0.38) and band-2(corressponding

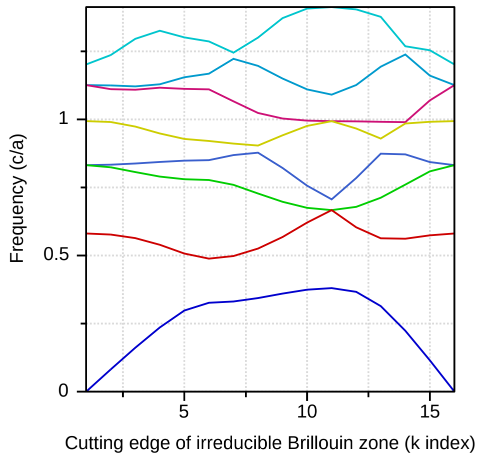

Figure 1: Photonic Band-Gap Diagram

to $\frac{a}{\lambda}$ of 0.48-0.55), where the propagation constant k_z has a value of 11.

The designed structure is a line defect tapered towards the length of the defect, guiding light at the above mentioned wavelength. This defect is obtained by suitable radius modifications or removal of a row of silicon rods. Hence, the radius 'r' of the rods and the lattice unit 'a' vary proportionately throughout the taper such that 'r/a' remains constant always, with the nominal radius being 60nm and the nominal lattice unit being 500nm. The reduction of 'r' and 'a' is brought about in 10 steps, each step being a 10 percent reduction from the previous value. Experimental fabrication of lattice structures with sub-100nm radius has been reported in [22]. The structure operates at the band-gap corresponding to $\frac{a}{\lambda}$ value of 0.4, where "a" is the lattice constant and λ are the appropriately available operating wavelengths which are obtained in and around $\lambda = 400n$m in the visible (violet) region and parts of the near-ultraviolet spectrum.

The Maxwell's equations for simple isotropic dielectric material, without any source are given in [23]. Considering periodic boundary conditions, fully - vectorial eigen modes of the Maxwell's equations are thus computed by preconditioned conjugate miniaturization of the block Rayleigh quotient in a planewave basis using MIT's open-source package MPB (MIT Photonic Bandgap) [23]. Based on this, the geometry of the structure is defined using the option of "polygons" available in the package Python-Meep [24] and is presented in Fig.(2).

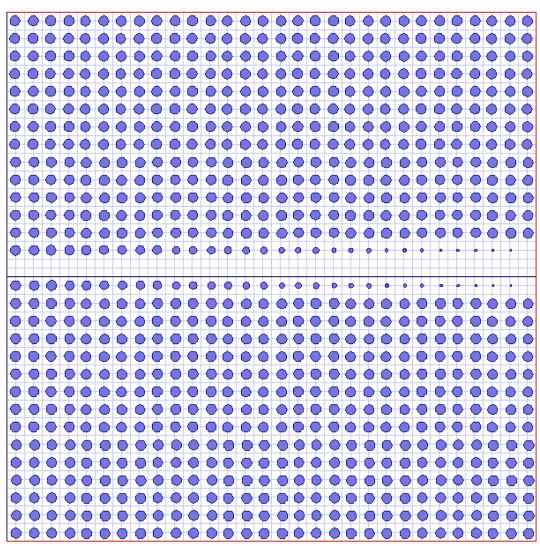

Figure 2: Structure as obtained from Python-MEEP Simulation

3. Results and Discussions

The input signal is a Gaussian pulse with a FWHM pulse width of 150fs. The power level of this input signal is relatively low, since structure-based nonlinearity is used. The input signal is initially launched through the narrow end of the taper, and hence this narrow end becomes the input port. The output signal is then observed at the broader end of the taper. The output of the Python-MEEP code is a “HDF5” file, which contains spatial and temporal information about the electric and magnetic fields. This file is then read using a MATLAB code and the corresponding surface plots are obtained. The surface plot corresponding to the final timestep for the above-mentioned observation is shown in Fig.(3) and the corresponding contour plot is shown in Fig.(4).

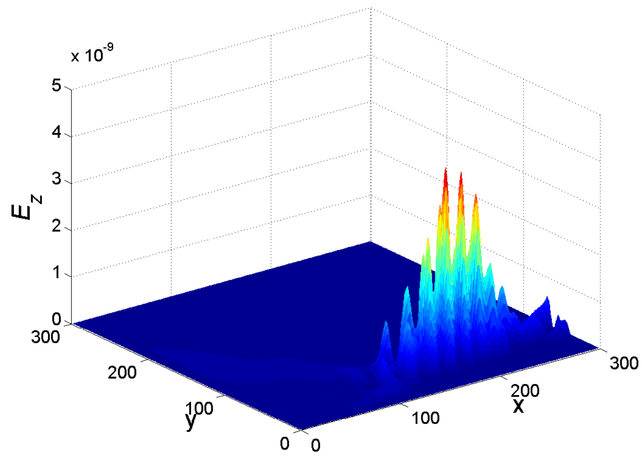

Figure 3: Surface Plot at final timestep, showing the formation of light bullets

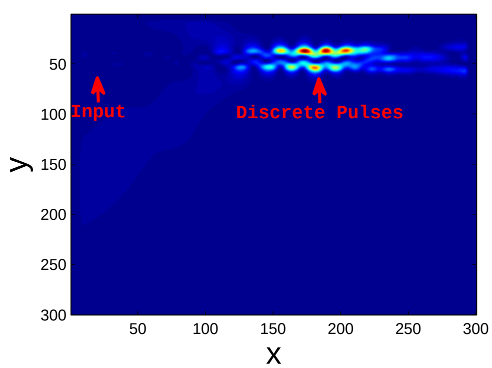

Figure 4: Two-Dimensional Contour plot at final timestep, showing the formation of light bullets

As can be seen from Fig.(3), half-way through the taper, one observes discrete pulses, or light bullets being formed. This is a result of the field confinement as mentioned earlier. This result is a consequence of a structure-based nonlinear waveguide in a linear photonic crystal created by the designed taper defects. A similar result has been mentioned in [25], but on employing a completely-nonlinear photonic crystal waveguide. Also one observes that there is relatively huge amplification of the order of 1000, at this point. The pulse compression and consequent adiabatic amplification can be explained by the fact that the effective refractive index changes along the length of the taper, and hence the dispersion monotonically decreases. These spatially confined discrete pulses form one of the main results of the paper, and such discrete pulses potentially find application as spatial memory elements, the taper structure acting as a memory writing device. A similar numerical experiment is made, but this time, the input signal is launched at the wider end of the defect. Hence the position of the input and output ports are reversed. The surface plot corresponding to the final timestep for the above-mentioned observation is shown in shown in Fig.(5). From Fig.(5), one sees that for the case where the input and output positions have been reversed, perfect attenuation is observed midway through the taper, attenuation being the exact complementary action of amplification. Here again, discrete pulses are observed close to the perfect attenuation point. Such a structure can hence potentially act as an optical matched termination. One also

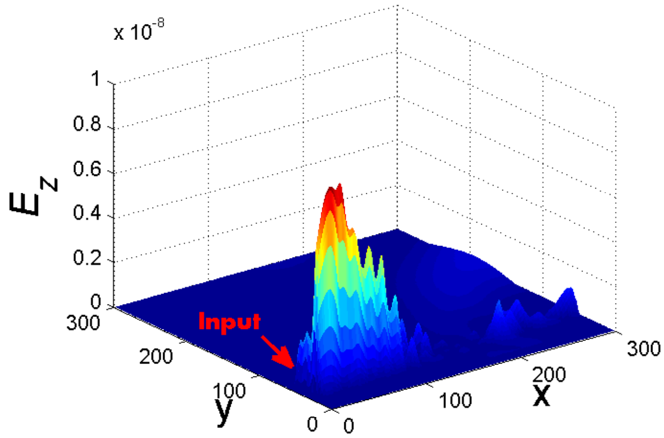

Figure 5: Surface Plot at final timestep, showing the perfectly matched attenuation

observes that in either case, one gets a pulse compression (blue-shifting of the Gaussian pulse), and hence with the pulse getting compressed, higher data rates can potentially be achieved. Such phenomena have been extensively reported in optical fibers[26, 27], and such pulse compressions find extensive application in high datarate communication systems.

A leakage analysis of the structure is done by performing a two-dimensional autocorrelation trace which is plotted in Fig.(6), from which one can ascertain the minimal leakage observed throughout the designed structure. Figures(7) and

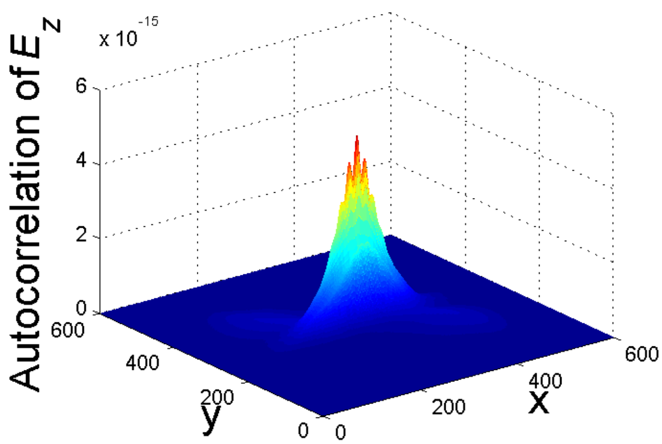

Figure 6: Two-Dimensional Autocorrelation

(8) show the pulse at the midway point of the taper structure, plotting the amplitude as functions of time and frequency respectively. As can be observed, the FWHM of the pulse is much smaller than 150fs, which further confirms the pulse compression. Figure (9) shows the surface plot at final timestep for the case where the length of the taper is designed in such a way that perfect field confinement does not occur. In such a structure, formation of discrete solitons do not occur. Nevertheless, pulse compression coupled with adiabatic amplification do occur, and such structures can play a crucial role in optical frequency upconverters and amplifiers.

While the formation of discrete pulses at the mid-point of the taper defect is indeed an interesting observation, it would be more useful if such discrete pulses are obtained at the end of the defect, where these light bullets can be tapped using appropriate waveguides. For this purpose, a structure containing the taper defect of 30 lattice units as discussed above, but with appropriate cavity defects at the mid point of the taper, as well as the end of the taper defect is designed, as shown in Fig. (10).

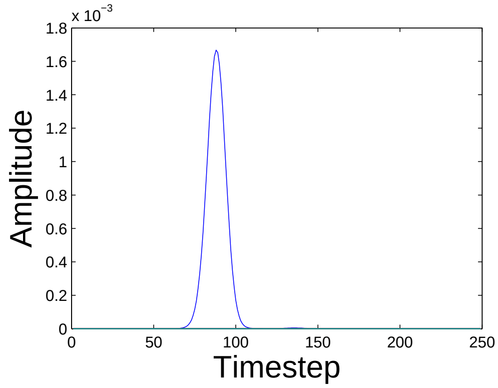

Figure 7: Output Pulse in time-domain. Here 1 Timestep = 5fs

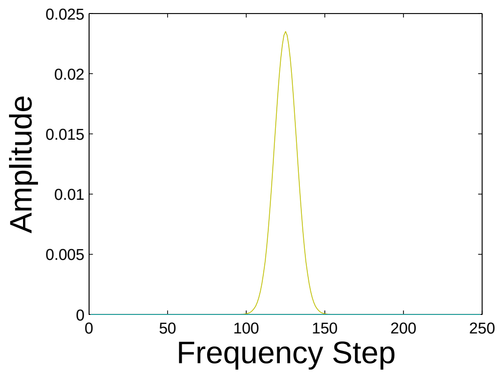

Figure 8: Output Spectrum in frequency-domain.

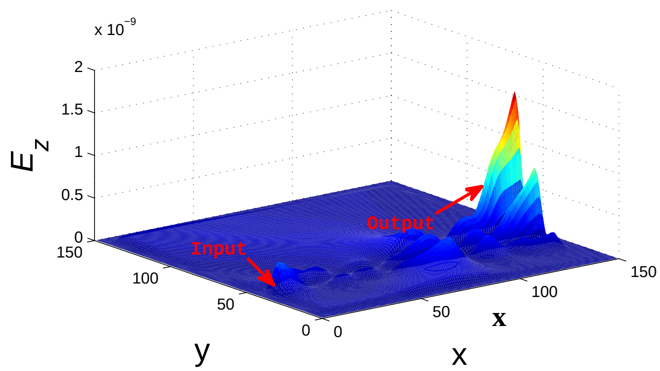

Figure 9: Surface Plot at final timestep, showing adiabatic amplification

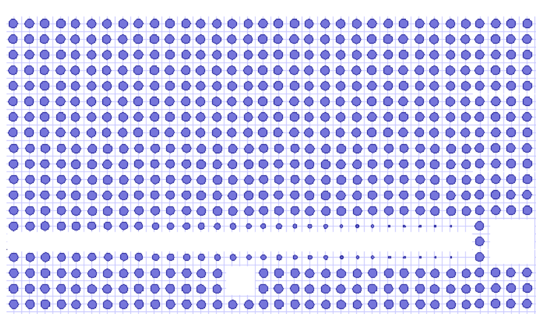

Figure 10: Structure based on Taper and Cavities, polygon structure obtained from python-meep simulation

The final timestep surface plot obtained for this structure is shown in Fig. (11), where a Gaussian pulse of FWHM 150fs has been launched at the cavity adjacent to the midpoint of the taper defect, termed the ‘control cavity’.

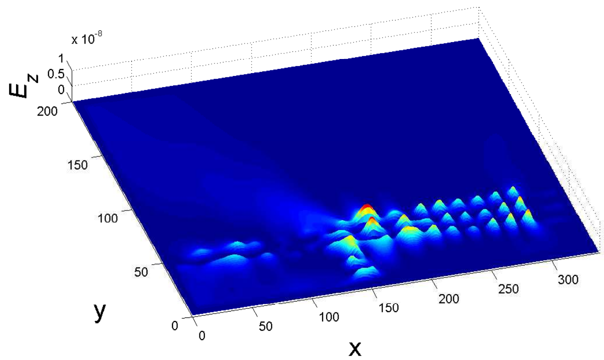

Figure 11: Field Distribution of taper defect based design with control cavities

It is seen that the signal launched in the control cavity is able to manipulate the flow of the Input signal, causing the discrete light bullets to ‘tunnel’ through the end of the taper defect and appear in the 3x3 array of cavities at the end of the structure. In this respect, the control cavity is analogous to the Gate terminal of a Field Effect Transistor, and to understand the Transfer Characteristics of this design, the Output Power is plotted as a function of Gate Power in Fig. (12), both powers being normalized to the input peak power.

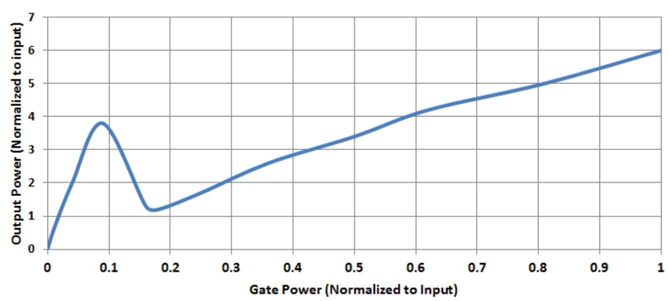

Figure 12: Transfer function of ‘photonic transistor’ showing bistability

It is seen that the Gate-Output Transfer curve shows signs of bistability, with the presence of negative slope in between two positive slope segments.

4. Conclusion

By proposing a two-dimensional linear photonic cystal manoeuvered by a lattice of silicon rods in air with a bandgap in the visible and near-ultraviolet spectra, a monotonically varying tapered line defect is introduced, pertaining to a case of structure-based nonlinearity, thereby operating in low input powers. For certain defect lengths, pulse compression and consequent adiabatic amplification is seen, along with bunching/anti-bunching of pulses. A detailed leakage and distortion analysis is made for this case. Moreover, for particular modes of operation, field confinement occurs, thereby resulting in the formation of discrete pulses, or optical bullets. The reversal of the positions of the input and output produce the exact complementary effect i.e. perfect attenuation. Hence, such a structure, acting as a multi-functional device, finds a plethora of diverse applications such as optical non-pumped amplification, frequency upconversion, memory writing, matched termination and slow wave guiding, that form the major conclusions of the work. Future work includes designing of three-dimensional extensions to the tapered structure, which might result in memory retrieving devices and dense memory storage devices.

References

[1] B.C.Kress and P.Meyreuis, *Applied Digital Optics-From Micro-optics to Nanophotonics*,(Wiley, UK, 2009).
[2] Jean-Michel Lourtioz, *Photonic crystals-Towards Nanoscale Photonic Devices* ,(Springer, Berlin, 2008).

[3] M.Skorobogatiy and J.Yang , *Fundamentals of Photonic crystal Guiding*,(Cambridge Uniersity Press, New York, 2009).
[4] J.D Joannopoulos,S.Johnson,J.N.Winn and R.Meade , *Photonic Crystals - Molding the flow of light*,(Princeton Uniersity Press, Singapore, 2008).
[5] I.A.Sukhoivanov and I.V.Guryev, *Photonic crystals - Physics and Practical Modeling* ,(Springer, Berlin, 2009).
[6] K. Busch, G. von Freymann, S. Linden, S.F. Mingaleev, L. Tkeshelashvili and M. Wegener, Phys. Rep. **444**, 101(2007).
[7] S. Assefa, S.J. McNab and Y.A. Vlasov, Opt. Lett. **31**, 745(2006).
[8] D.Englund, A.Majumdar, M.Bajcsy, A.Faraon, P.Petroff, and J.Vuckovic, Phys. Rev. Lett. **108**, 093604(2012).
[9] Y. Chassagneux1, R. Colombelli, W. Maineult, S. Barbieri, H. E. Beere, D. A. Ritchie, S. P. Khanna, E. H. Linfield and A. G. Davies, Nature **457**, 174(2008).
[10] Y.A.Vlasov, M.O'Boyle, H.F.Hamann and S.J.McNab, Nature **438**,65(2005).
[11] Henning Schomerus and Nicole Yunger Halpern, Phys. Rev. Lett. **110**, 013903(2013).
[12] A. Blanco, E. Chomski, S. Grabtchak, Nature,**405,**437(2000).
[13] K.Ishizaki and S.Noda, Nature **460**, 367(2009).
[14] J. D. Joannopoulos, P.R.Villeneuve and S.Fan, Nature **386**,143(1997).
[15] J.Xu, X.Zhang, Y.Zhang, J.Dong, D.Liun and D.Huang, IEEE J.Lightwave Tech.,**27,**5268(2009).
[16] Andrey A. Sukhorukov, Sangwoo Ha, Kokou B. Dossou, Lindsay C. Botten, Andrei V. Lavrinenko, Dmitry N. Chigrin and Yuri S. Kivshar, Opt. Lett. **36**, 1170(2011).
[17] K. Kondo, M. Shinkawa, Y. Hamachi, Y. Saito, Y. Arita, and T. Baba, Phys. Rev. Lett. **110**, 053902(2013).
[18] P.Bienstman, S.Assefa, S.G.Johnson, J.D.Joannopoulos, G.S.Petrich and L.A.Kolodziejski, J. Opt. Soc. Am. B **20**, 1817(2003).
[19] A.S.Scherbakov and A.A.Lopez, Revista Mexicana de Fisica **53**, 96(2007).
[20] P.L.Chu, Y.S.Kivshar, B.A.Malomed, G.D.Peng and M.L.Quiroga-Teixeiro, J. Opt. Soc. Am. B **12,**898(1995).
[21] H.Kurt and D.S.Citrin, Appl. Phys. Lett.,**87**, 041108, 2005.
[22] X. Wang, C.Neff, E.Graugnard, Y.Ding, J.S.King, L.A.Pranger, R.Tannenbaum, Z.L.Wang and C.J.Summers, Adv. Mater. **17**, 2103(2005).
[23] A.F.Oskooi, D.Roundy, M.Ibanescu, P.Bermel, J.D Joannopoulos, and S.Johnson, Computer Physics Communications, **181,**687(2010).
[24] E.Lambert, M.Fiers, S.Nizamov, M.Tassaret, S.G.Johnson, P.Bientsman and W.Bogaerts, IEEE Computing in Science and Engineering,**13,**53(2011).
[25] Y.S.Kivshar and G.P.Agrawal, *Optical Solitons - From fibers to photonic crystals*, (Academic Press, San Diego, 2003).
[26] Jan Rothhardt, Steffen Hdrich, Henning Carstens, Nicholas Herrick, Stefan Demmler, Jens Limpert, and Andreas Tnnermann, Opt.Lett.**36,**4605(2011).
[27] S. P. Stark, A. Podlipensky, and P. St. J. Russell, Phys. Rev. Lett. **106**, 083903(2011).