Enhanced EO Wavelength Conversion Using Slow Light

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Abstract

Slow light in photonic crystals can be used to increase the efficiency of nonlinear processes. The increased electric field near internal resonances increases the efficiency of parametric interactions such as harmonic up-conversion and down-conversion to the IR, and provides a versatile method for phase-matching. This review describes the theoretical background and experimental results reported in recent literature for semiconductor photonic crystals, optical fibres and waveguides. Prospects for efficient parametric converters with low pump power requirements are discussed.

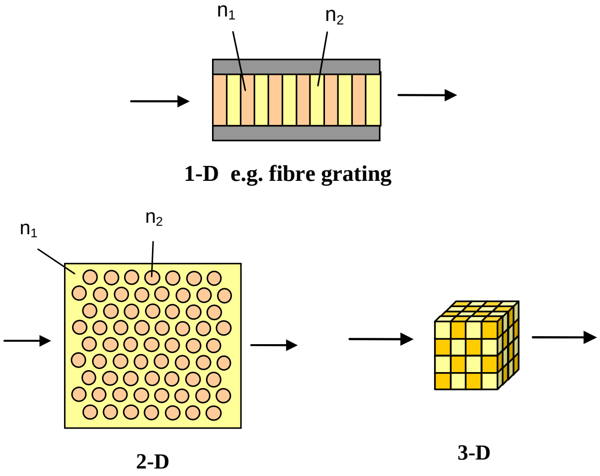
Introduction

Several widely different techniques for reducing the velocity of light in optical materials have been demonstrated in recent years, and have stimulated interest in applications to optical signal processing and nonlinear optics [1-4]. Velocity reductions down to a few metres per second have been observed in atomic gases at low temperature [1], but practical applications require solid-state media at room temperature which restricts the field to various forms of photonic crystal. The interest in slow light for non-linear optics arises from the increased electric field inside the material, and consequent increase in nonlinear effects, and the ability to adjust the refractive index dispersion over a wide range to provide accurate phase matching over long path lengths. This paper reviews the theoretical background, recent results reported in the literature and prospects for future development.

Slow Light in Photonic Crystals

Photonic crystals are dielectrics containing periodic refractive index variations in 1, 2 or 3 dimensions. Examples shown in fig 1 are an optical fibre grating, a medium containing a 2-D array of rods having a different refractive index, and a 3-D array of dielectric spheres or cubes. If the spatial period is less than the wavelength of light, the propagation wave vector is strongly dependent on the wavelength and the direction of propagation [5], so that materials exhibit variable group velocities depending on wavelength and direction. In certain frequency ranges there are “band gaps” associated with optical resonances, where no propagation is possible. The group velocity is greatly reduced close to band gap edges, and the electric field is increased, causing an increase in nonlinear effects.

Conventional nonlinear materials like $LiNbO_3$ require special techniques like birefringent compensation or periodic poling to achieve phase matching. Using the variable velocity dispersion close to band gap edges, photonic crystals offer a more generally applicable alternative which can greatly extend the range of useful materials to include highly dispersive crystals [6], amorphous materials [7], optical fibres [8] and semiconductors [9,10]. Alternative EO materials more compatible with other optical technologies such as semiconductor lasers, integrated optics and optical fibres can be used for wavelength conversion.



1-D e.g. fibre grating

2-D

3-D

Fig 1 1, 2 and 3-dimensional photonic crystals

Periodically-poled Materials

Periodically-poled crystals, like lithium niobate (PPLN) [11] and lithium tantalate [12] have been used for some time to improve the efficiency of parametric converters. The poling direction is periodically reversed to cancel the dispersion, and so maintain efficient conversion over a long path. They can be regarded as 1-dimensional photonic crystals in which an additional wave vector contributed by the crystal periodicity balances the wave vector differences between input and output. 2-D periodically poled crystals are even more versatile, providing angle-tuning to optimise phase matching, and reducing the sensitivity to temperature [10,13]. The grating spacing is typically much larger than the optical wavelength, (10-30μm), so photonic resonances are far removed from input and output wavelengths. Consequently there is no resonant enhancement of the electric field, and no increase in nonlinear effects from this cause. The advantage of periodic poling is that phase-matched operation is possible in any crystal direction, enabling the large d_{33} coefficient in materials like $LiNbO_3$ and $LiTaO_3$ to be efficiently used.

Nonlinear Optics in Photonic Crystals

Most demonstrations of nonlinear photonic crystals have used 1-D structures because of their analytical simplicity and the relative ease of fabrication in optical waveguides. Devices have been made in optical fibres [15,16], in EO waveguides in lithium niobate, and in semiconductors such as silicon, GaAlAs and GaN [9,10,14,17].

Second harmonic generation (SHG) is usually only possible in non-centro-symmetric crystals such as $LiNbO_3$, but the centre of symmetry is broken in photonic crystals at the interfaces between media, making normally isotropic materials like silica, amorphous semiconductors and plastics possible alternatives.

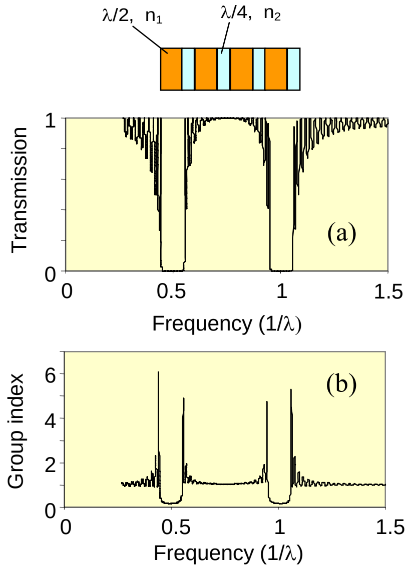


Fig 2 Transmission and group refractive index for a 1-D photonic crystal (a) transmission, (b) group refractive index

The periodic modulation of refractive index produces a series of resonances at frequencies where the optical wave vector (2π/wavelength) is harmonically related to the grating wave vector. A theoretical example in fig 2 shows the transmission and group refractive index for a 1-D grating consisting of 20 alternate half and quarter-wave layers of high and low refractive index (1.5 and 1.0), using the design formulae for thin film stacks [18]. Fig 2(a) shows the transmission as a function of frequency, with band gaps at frequencies of $0.5/\lambda_0$ and $1.0/\lambda_0$, and the group refractive index is plotted in fig 2(b). This is the ratio of the light velocity in vacuum to the group velocity $\partial\omega/\partial k$ where ω is the angular frequency and k is $2\pi/\lambda_0$. At the edges of the band gaps, the effective index rises rapidly, and the group wave velocity falls, leading to a large increase in the electric field. Pumping the crystal with light at a frequency close to the lower band edge generates a second harmonic close the frequency of the upper band edge, so both the fundamental and second harmonic have increased amplitudes. Owing to the quadratic dependence of second harmonic conversion on the electric field, this results in a very large increase in conversion efficiency, provided that the phase matching condition is fulfilled.

Several studies of the second harmonic generation process, based on 1-D models have been reported. Scalora et al [16,19] have modelled SHG in a structure similar to fig 2, by solving the EM field equations for pulse propagation using a coupled mode approach. Results show that when both the pump and the second harmonic are close to band edges, the increased mode density ensures that phase matching can be achieved, resulting in a relative increase in SHG power by 2-3 orders of magnitude.

Harmonic Generation in Semiconductors

1-D photonic crystals can be formed in semiconductor heterostructures by growing a stack of layers of different refractive index, such as the early experiments reported some time ago by Bell Laboratories using GaAs-$Al_{0.3}Ga_{0.7}As$ [14]. Their device consisted of a stack of 34 layers, each a quarter-wavelength thick at 2.0μm. Only the pump wavelength was resonant in this case. The second harmonic was in the high transmission region between resonances, so only a relatively low SHG enhancement of 10-20 was obtained. This structure is shown in fig 3.

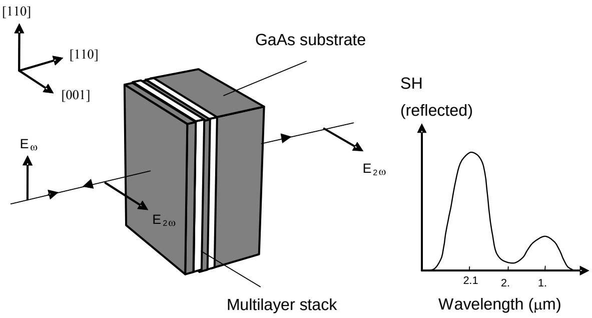


Fig 3 Second harmonic generation in GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructure [14]

Both forward and backward SHG waves were generated, but only the backward wave was phase-matched, and the forward wave was largely suppressed. There was a strong resonant enhancement of the second harmonic around 2.1μm, on the long wavelength side of the band gap, and a smaller one on the short wavelength side, with little in between where the band gap was strongly absorbing.

The nonlinear coefficient in GaAs/GaAlAs is small, producing a low photonic resonance Q-factor. Much greater SHG enhancement has been observed in GaN which is non-centrosymmetric and has a significant d_{33} coefficient of 4.5pm/V [9]. This structure consisted of a GaN layer grown on a sapphire surface, forming a planar waveguide. A ribbed grating of GaN stripes was grown on the surface, as shown in fig 4.

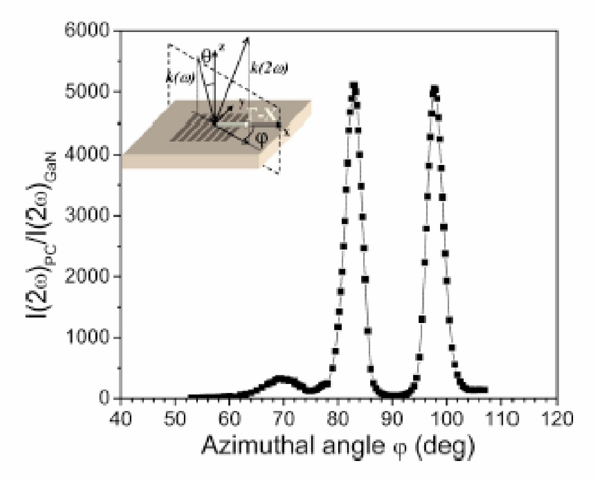


Fig 4 Enhanced SHG in GaN planar photonic crystal [10]

Optimum tuning and phase matching was achieved by varying the angle of incidence θ. of the pulsed 791nm input beam, and the azimuth angle ϕ, and measuring the reflected second harmonic power. This gave the result shown in fig 4. The maximum second harmonic power was 5000 times larger than that obtained from the unpatterned GaN layer, demonstrating the effectiveness of using double resonance and angle-tuning. This was 50 times larger than the gain achieved in the singly-resonant Bell Labs device. The path length in this device was very short so the conversion efficiency was very low. Structures with a much longer interaction length are needed to get useful conversion efficiencies.

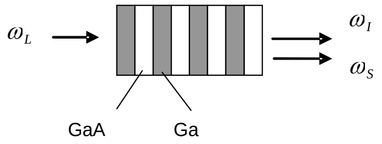
Optical Parametric Oscillators

In a parametric oscillator, a pump laser frequency ω_L is down-converted in a nonlinear medium into two lower frequencies, the signal and the idler, at ω_S and ω_I respectively. The conditions for frequency and phase matching are that

$$\omega_L = \omega_S + \omega_I$$

$$k_L = k_S + k_I \pm nG$$

where k_L, k_S and k_I are the wave vectors of the pump, signal and idler, G is the wavevector contributed by the photonic crystal and n is an integer. Some theoretical examples of parametric down conversion are given in [14] for a heterostructure consisting of quarter wave layers of GaAs and GaP which has the band structure shown in fig 5. These figures are for layers 2μm thick which resonate in the 10μm band, but similar performance at shorter pump wavelengths should be obtainable with thinner layers, provided all wavelengths are within the transmission range of the materials. The material itself is opaque within the range 237 – 401cm^{-1}, and the photonic band gap in this case is located at approximately 800cm^{-1}. The first example is for an OPO converting 10μm pump radiation into a tuneable signal beam covering 15-25μm, and a far-IR OPO converting a 10μm pump to tuneable terahertz radiation around 30–100cm^{-1} (1–3THz).



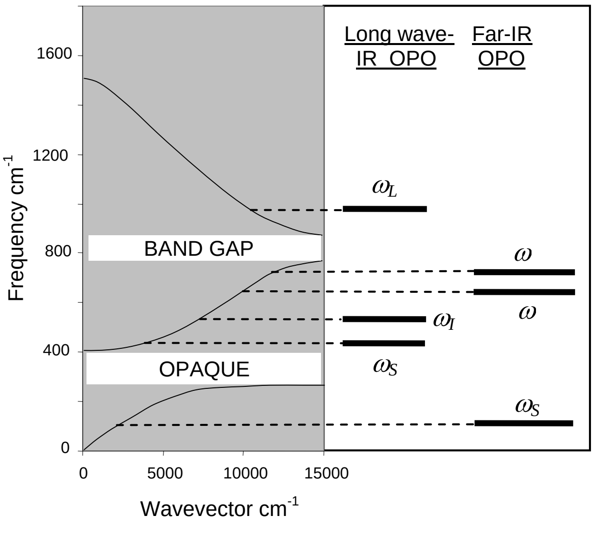


Fig 5 Dispersion curves for GaP:GaAs and wavevectors for mid–IR and far–IR OPOs [14]

Tuneable OPOs need to be singly-resonant at the pump frequency, so the overall enhancement in conversion efficiency is likely to be limited to 10-100. Efficient converters in the far-IR are important because there are few other CW sources of tuneable radiation in the terahertz region.

The 0.3-3THz range, where the atmosphere is partially transparent, is used for terahertz imaging, which is of value for security and defence.

Wavelength Conversion in Optical Fibres

Large nonlinear coeffcients can be created in poled germano-silicate optical fibres by applying a large electric field at the same time as exposing them to a UV grating. Coefficients as large as 6pm/V have been found [20] comparable with conventional EO crystals. The maximum index modulation achievable is <1%, so long gratings with narrow resonance bandwidths are needed to achieve a large electric field enhancement.

One-dimensional models [21, 22] show that enhanced second harmonic output is obtained when the grating is close to resonance either at the fundamental or the second harmonic. The maximum second harmonic gain occurs when the wavelength is tuned within a very narrow band (<1nm) close to the band gap edge. Roughly equal SHG powers are created in both directions, so the two output beams need to be combined by external optics to achieve maximum power conversion.

The core diameter limits the power handling capability of fibres, so CW or quasi-CW wavelength converters at a power level of watts are possible, but not high power pulses. IR absorption in silica limits the wavelength range of parametric down-converters to about 2μm.

Photonic Crystals with Periodic Defects

Larger reductions in group velocity in narrow wavelength ranges can be obtained by incorporating periodic defects into the lattice. Each defect constitutes a small resonator, so weak coupling between defects creates a very slow group velocity. For example, the structure in fig 6 consists of half-wave layers of a high refractive index sandwiched between quarter-wave reflective stacks, creating in effect a sequence of weakly coupled Fabry-Perot etalons. The low group velocity is illustrated in fig 6 for 10-layer reflectors of ZnS and LiF.

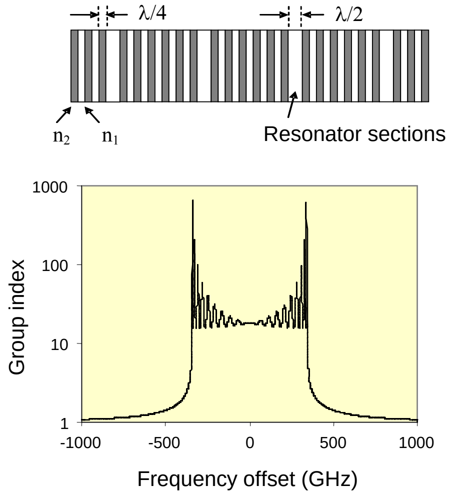


Fig 6 Group refractive index of photonic crystal containing periodic defects.

A group index >100 is achievable close to the band gap edge. The electric field is strongly increased in the half-wave layers by >100 times, leading to a local increase in EO conversion efficiency >10,000. The fundamental limits on conversion efficiency will be the breakdown strength of the half-wave sections, and electro-optic detuning of the resonance. The effect has been demonstrated using a nonlinear layer of dye molecules sandwiched between thin film multilayer reflectors forming low-Q resonators [29]. The SHG power in reflection was enhanced by about one order of magnitude compared with a non-resonant medium. The low efficiency was due mainly to absorption in the dye.

2-dimensional structures similar to this have been made in silicon using a planar waveguide formed in polysilicon on top of a SiO_2 layer shown in fig 7 [24]. Arrays of holes were etched in the silicon through an e-beam mask, and every third hole was missed out, forming an array of micro-resonators in a photonic crystal. Q-factors >1000 and group velocities <c/100 have been achieved.

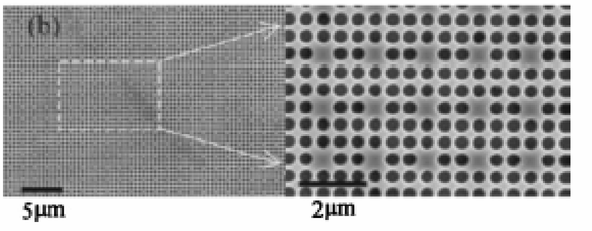


Fig 7 Two-dimensional photonic crystal containing an array of coupled microcavities [26]

The array has the same wave velocity in X and Y directions so the need to focus the pump beam is greatly reduced, making coupling to external optics much easier. The main application envisaged in [26] for these structures is slow delay lines for signal processing, but large nonlinear coefficients can be induced by poling amorphous materials as described in [20], so enhanced nonlinear effects should be possible in structures of similar construction.

3-D Photonic Crystals

Even more relaxed focusing requirements should be achievable in 3-D photonic crystals with defects regularly spaced in all directions, as well as having much larger optical aperture and power handling capability. A possible technique for constructing large 3-D crystals with uniformly-spaced defects is deep directional etching of silicon [25].

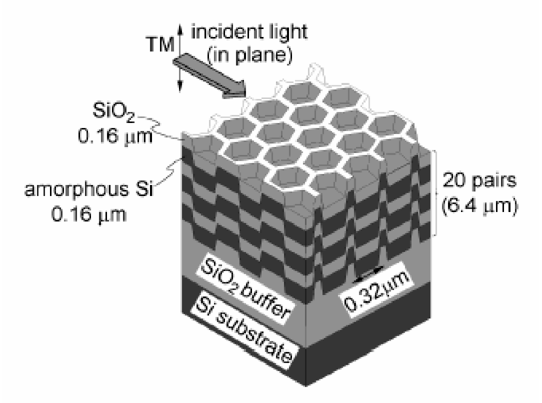
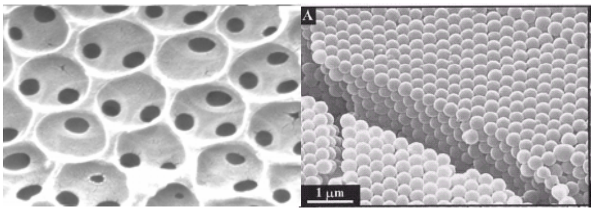


Fig 8 Self-formed 3-D photonic crystal on patterned Si substrate, Kosaka [27]

Another possibility is to stack planar 2-D crystals one on top of the other with the correct spacing between them. Some small experimental devices using depositions of polysilicon and SiO_2 have been constructed by repeated deposition and masking operations [26, 27] (fig 8). The process is laborious, and does not lend itself to the formation of large crystals with tight spacing tolerances.

A more practical approach for large crystals is “self-assembly”, which involves assembling regular stacks of sub-micron dielectric spheres, and filling the spaces between them with a material having a different refractive index. Large samples have been made by depositing uniform layers of sub-micron silica spheres on a glass plate using evaporation from a colloidal suspension [28]. Silica in not the ideal electro-optic material, but having formed a 3-D matrix with silica microspheres, moulding and casting methods can be used to replace the silica with a more highly active nonlinear material. This is shown in fig 9, where the air spaces between spheres have been back-filled to form a polymer template when the silica is dissolved away. This is then filled with a suitable precursor from which a high-index material such as TiO_2 can be chemically deposited. The result is a casting with the same 3-D geometry as the original matrix.



(a) Macroporous template

(b) Cast of polymerised TiO_2 spheres

Fig 9 3-D photonic crystal formed in high-index material by casting from macroporous polymer template

Second harmonic generation from a 3-D photonic crystal of this kind has been reported in [29]. Hydrophobic latex microspheres of 0.115µm diameter were coated with a polar dye molecule with a high nonlinear coefficient. Particles were deposited under gravity from a colloidal suspension, forming a uniform single crystal 50×10×1mm, a process which took four days. Phase matching between a pulsed 1064nm pump laser and the 532nm second harmonic was achieved by angle-tuning the crystal close to the (111) planes of the face-centred cubic crystal. For a 1mm thick sample, an enhancement in SHG power of about one order of magnitude over a similar non-crystalline structure was observed. The highest SHG output was observed in the backward travelling wave. The forward wave was absorbed to some extent by the green dye forming the nonlinear medium.

It is possible that performance could be improved further using an alternative dyestuff. Alternatively the nonlinear coefficient on the microspheres could be enhanced by poling applied after manufacture using a high electric field with elevated temperature, in a similar manner to process used successfully on silica/germania optical fibres [20].

Conclusions

The effective non-linear coefficients of optical materials can be increased several thousand times by slowing the velocity of light in photonic crystals. Experiments in small semiconductor and waveguide devices have demonstrated the enhanced conversion efficiency, and the ability of photonic resonances to phase-match input and output waves. This technology should enable efficient optical harmonic generators and parametric oscillators to be constructed using lower power pump lasers, and a wider range of nonlinear materials.

An increase in second harmonic power by 5000 times has been observed in GaN semiconductors with 1-dimensional gratings resonant at both the pump and second harmonic wavelengths. Large increases have also been observed in optical fibres containing Bragg gratings. Output powers obtained so far have been small owing to the small interaction lengths, but the principle of using wavelength and angle-tuning to simultaneously optimise both the nonlinear response and phase matching can be applied to larger, more efficient devices.

Recent demonstrations of 2-D photonic crystals incorporating resonator arrays, and 3-D self-assembled photonic crystals offer the possibility of constructing parametric devices in a range of new materials with larger optical apertures and power handling capability. They could be used for efficient, low power harmonic generators and tuneable down-converters for the 3-5µm, 8-12µm and terahertz regions of the spectrum.

References

1. Chie Liu et al. *Observation of coherent optical information storage in atomic medium using halted light pulses*, Nature, Vol 409, 25th Jan 2001, p490.
2. M S Bigelow et al, *Superluminal and slow light propagation in room temperature solid*, Science, Vol. 301, No 5630, p200-2 11th July 2003.
3. H Altug et al, *Experimental demonstration of the slow group velocity of light in two-dimensional*

coupled photonic crystal microcavity arrays, Appl Phys Lett, **86**, p111102, (2005).

4. J B Khurgin, *Optical buffers based on slow light in electromagnetically induced transparent media and coupled resonator structures: a comparative analysis*, J Opt. Soc Am. B, **22**(5), May 2005, p1062
5. J. D. Joannopoulos et al, *Photonic Crystals*, Princeton University Press, 1995
6. Boquin Ma et al, *Effect of different quasi-phase matchings in two dimensional nonlinear phonic crystal*, Jap. J. Appl. Phys. **43**(6A), 2004, pp 3397-3400.
7. Hideyuki Inouye et al, *Optical properties of total-reflection-type one-dimensional photonic crystal*, IEEE J of Quantum Electronics, **38**(7), 7th July 2002, p867-871.
8. M. J. Steel et al, *Second harmonic generation in second harmonic fibre Bragg gratings*, Appl. Opt. **35**(18), 20 June 1995, pp3211-3221.
9. J. Torres et al, *Giant second harmonic generation in one-dimensional GaN photonic crystal*, Physical Review B **69** 085105 (2004).
10. J. P. van der Ziel et al, *Optical second harmonic generation in periodic multilayer* $GaAs\text{-}Al_{03}Ga_{0.7}As$ *structures*, Appl. Phys. Lett. **28**(8), 15 April 1976, pp437-439.
11. L. E. Myers et al, *Quasi-phase-matched optical parametric oscillators in bulk periodically poled* $LiNbO_3$, J. Opt. Soc. Am. B, **12**(11), Nov 1995, pp 2102-2116.
12. Shi-ning Zhu et al, *Second harmonic generation of blue light in bulk periodically poled* $LiTaO_3$, Appl. Phys. Lett. **67**(3), 17 July 1995, pp 320-322.
13. N. G. R. Broderick et al, *Temperature and wavelength tuning of second-, third- and fourth-harmonic generation in a two-dimensional hexagonally poled nonlinear crystal*, J. Opt. Soc. Am. B. **19**(9), Sept 2002, pp 2263-2272.
14. N. Bloembergen et al, *Nonlinear optical properties of periodic laminar structures*, Appl. Phys. Lett. **17**(11), 1 Dec 1970, pp 483-486.
15. J. W. Haus et al, *Enhanced second-harmonic generation in media with weak periodicity*, Phys. Rev. A, **57**(3), March 1998, pp 2120-2128.
16. M. Scalora et al, *Pulsed second harmonic generation in nonlinear, one-dimensional, periodic structures*, Phys. Rev. A, **56**(4), Oct. 1997, pp3166-3174.
17. Y. Dumeige et al, *Enhancement of second-harmonic generation in a one-dimensional semiconductor photonic band gap*, Appl. Phys. Lett. **78**(20), 14 May 2001, pp3021-3023.
18. M. Bass (ed), *Handbook of Optics*, Ch 42, Optical Society of America, 1995.
19. M. Centini et al, *Dispersive properties of finite, one-dimensional photonic band gap structures: Applications to nonlinear quadratic interactions*, Phys. Rev. E, **60**(4), Oct. 1999, pp 4891-4898.
20. T Fujiwara et al, *Electro-optic modulation in germanosilicate fibre with UV excited poling*. Electronics Letters, **31**(7), 30th March 1995, p573-4.
21. Jianping Shi et al, *Analysis of optical SHG in photonic crystal consisting of centro-symmetric dielectric*, Optics Express, **12**(22), 1 Nov. 2004, pp5307-5313.

22. C. De Angelis et al, *Conversion efficiency for second harmonic generation in photonic crystals*, J. Opt. Soc. Am, B **18**(3), March 2001, pp348-351.
23. J Trull et al, *Second harmonic generation in local modes of a truncated periodic structure*, Optics Letters, **20**(17), 1 September 1995, pp1746-1748.
24. H Altug et al, *Experimental demonstration of the slow group velocity of light in two-dimensional coupled photonic crystal microcavity arrays*, Appl. Phys. Lett. **86**, 111102 (2005)
25. S. Matthias et al, *Three-dimensional structuring of silicon for photonic crystals with complete photonic band gaps*, Photonic Crystals materials and Devices III, January 2005, Proc. SPIE, Vol. 5733, pp1-11.
26. Y Ohtera et al, *Waveguide and guided wave devices consisting of heterostructured photonic crystals*, Optical Engineering, **43**(5), p1022-1029, (May 2004)
27. H. Kosaka et al, *Photonic crystals for micro lightwave circuits using wavelength-dependent angular beam steering*, Appl. Phys. Lett. **74**(10), 8 March 1999, pp1370-1372.
28. T. Prasad et al, *Superprism phenomenon in three-dimensional macroporous polymer photonic crystals,* Phys. Rev. B **67**(16) 2003, p 165103
29. J. Martorell et al, *Second harmonic generation in a photonic crystal*, Appl. Phys. Lett. **70**(6), 10 February 1997, p702