Introducing Triangular Lattices to Dynamic Photonic Crystal Structures for Optical Storage and Processing

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***Abstract*–A dynamic photonic crystal structure based on a triangular lattice and GaAs is proposed for optical storage and processing. Preserving the translational invariance and the adiabaticity, the structure exhibits electromagnetic induced transparency and can compress larger bandwidth pulses than the previous square lattice models.**

***Index Terms*–Dynamic structures, temporal coupled mode theory, optical storage, refractive index modulation.**

I. INTRODUCTION

One of the important advances in the theory of photonic crystals (PhC) is the development of the dynamic PhC structures. They are basically coupled resonator array systems which can be constructed from two dimensional PhC structures. By modulating the refractive index of the system, it behaves as both a tunable bandwidth filter and a tunable delay element [1]. These properties allow for high capabilities to store and process optical information.

II. CONSTRUCTING THE MODEL

The basic system used to manipulate light pulses is shown in Fig.1. The unit cell of this translationally invariant system consists of a waveguide side coupled to two cavities [2]. The previously suggested model consists of a square lattice with refractive index of 3.5 and a radius of 0.2*a*, embedded in air ($n=1$), where ‘a’ is the lattice constant [2]. In this model, reducing both the refractive index and the radius of a single rod to 2.24 and 0.1*a*, respectively creates a single-mode cavity with resonance at $\omega_o=0.357(2\pi c/a)$ [2]. In the case of a triangular lattice at the same background rods of $\varepsilon=12.25$, the cavity refractive index should be reduced to 2.75 instead of 2.24. A cross section of the suggested system is displayed in Fig. 2. By modulating the refractive index of this system, the resonance frequencies of the unit cell cavities can be varied creating two cavities with resonance frequencies of $\omega_{1,2}=\omega_o\pm\delta\omega/2$ [3], $\delta\omega$ is the signal bandwidth. In the case of a triangular lattice, both cavities have the same symmetry and the system supports nonorthogonal modes [4]. This system exhibits electromagnetic induced transparency.

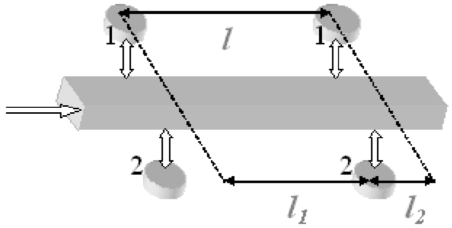

Fig.1. Schematic of two unit cells of the coupled-cavity structure used to stop light. The cavities couple to the waveguide with a coupling rate of $1/\tau_l$.The length of the unit cell is $l = l_1 + l_2$ [2].

III. MODEL ANALYSIS

A. Effect of Triangular Lattice

The triangular lattice presented in this work has an advantage of compressing larger bandwidths than that of the square lattice. In addition, the ratio of the final to the original bandwidths is to its advantage.

The reason for this is two fold: first, an introduced defect mode at the center of the gap is more localized in the case of triangular lattice because it is larger. Being on a logarithmic scale (results from the exponential nature of the evanescent modes) with the same final value of leaking into the extended bands, any deviation (represented by the refractive index modulation) is more effective in the case of the triangular lattice leading to a wider pulse bandwidth $\delta\omega$. Moreover, a better quality factor is, obtained in the case of the triangular lattice. Both the preceding factors can be introduced in the bandwidth $\Delta \equiv 2Q|\omega_1-\omega_2|/\omega_0$ leading to a higher compressible bandwidth.

B. Effect of Using GaAs

Using GaAs ($\varepsilon=11.4$ at $\lambda=1.55\mu m$) leads to larger compressible bandwidth than that obtained if the original material with $\varepsilon=12.25$ is used. For a material with $\varepsilon=12.25$, a

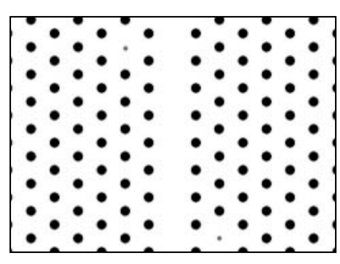

Fig. 2. Schematic of a two-dimensional triangular lattice photonic crystal structure with dielectric rods of radius 0.2a. Removing one row of dielectric rods creates a waveguide. In each unit cell, two single-mode cavities are created on opposite sides of the waveguide with a separation l_l=7a

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larger value for dielectric shift $\Delta\varepsilon$ is required for a defect mode to cross half the bandgap (which is large) and be introduced at the middle of the gap. On the other hand, in the case of GaAs, no such big effort is required because the bandgap is smaller. If the difference in the original value is small ($\Delta\varepsilon$=12.25-11.14) and this difference will be further reduced when the refractive modulation index is considered (Δn=3.5-3.37), the required dielectric constant for the defect cavity mode can be larger for GaAs (n_{cavity}=2.42) than in the case of ε=12.25 (n_{cavity}=2.24) at the same defect frequency. Once the defect mode is established, the perturbation theory and the variational theories can be applied, and the compressible bandwidth is larger in GaAs case.

C. Required Waveguide Length

The required waveguide length increases with the pulse bandwidth. This represents a drawback in using triangular lattice and GaAs.

D. Group-Velocity Dispersion

A waveguide carved in the bulk of PhC structure introduces a linear defect band. In the design of such structures, it is important to choose a linear region of operation to avoid pulse dispersion and distortion. A slope variation ($d^2\omega/dk^2\neq 0$) of the defect mode leads to a group-velocity dispersion. Although both structures offer good approximation to the linear operation, square lattice has less slope variation (less distortion.) than the square lattice.

The qualitative analysis given above is verified by the results obtained from FDTD simulations, the application of temporal coupled mode theory and transmission matrix approach.

Following the same refractive index modulation for all structures constructed in this work, simulation results can be summarized as follows. First, when the conventional dielectric constant is used (ε=12.25), the compressible bandwidths are Δ=3.189 and Δ=7.572 for the square and the triangular lattices, respectively. Upon modulating the refractive indices of the cavity dielectric rods, these bandwidths are compressed to Δ=0.329, and Δ=0.637, respectively. This corresponds to compression to 10.3% and 8.4% of the original bandwidth. Second, when GaAs is used instead, the compressible bandwidths are Δ=3.747, and Δ=10.129 for the square and the triangular lattices, respectively. These bandwidths are compressed to Δ=0.382, and Δ=0.984 with a corresponding compression ratios of 10.2%, and 9.7%, respectively. If the effect of using GaAs is considered, results show higher bandwidth compression capabilities. For a square lattice structure, using GaAs results in 17.5% increase in the bandwidth compressible over the conventional ε=12.25 material. Moreover, it can result in an increase in the compressible bandwidth up to 33.4% when a triangular lattice is used. This extra waveguide length requirement for the compression process depends mainly on Δ. As an example, for the system parameters previously studied [2] of square lattice at ε=12.25, the required waveguide length in is $L\approx(10+3.2*5)l$. where l is the length of a unit cell. Therefore, increasing Δ by $x\%$ requires increasing the length by $x*(3.2/5.2)\%$. The corresponding requirements are 85% (triangular lattice at ε=12.25), 11% (square lattice at ε=11.4), and 134% (triangular lattice at ε=11.4) increase in the waveguide length. It should be noted that this increase in the waveguide length will compensate for the extra band. i.e. the final compressed bandwidth and the pulse delay are the same for all systems. Moreover, using the same resolution, square lattice shows less slope variations than the triangular one. Many solutions can be suggested like reducing such dispersion, choosing the most linear region of operation, or optimizing the pulse shape (the dynamic process presented here is not affected by the pulse shape). However, investigating this point is beyond the scope of this work.

IV. Conclusion

Finally, this work is focused on the optimization of a dynamic PhC structure used for optical storage and processing. The main highlight is the introduction of the triangular lattice and the use of GaAs as the background dielectric material. In order to obtain similar propagation characteristics in different directions, a system with spherical Brillouin zone should be constructed. Photonic bandgap in one dimension opens up at the edges of the Brillouin zone. This happens even in the case of a small dielectric contrast. Spherical Brillouin zone has the same wave vector magnitude in all directions. The limiting case in 2D is a circular one. Triangular lattice offers a closer approximation to the circular Brillouin zone than the square one. GaAs is a material existing in nature with extensively studied properties. Qualitative analysis shows an increase in the compressible bandwidth of the proposed system upon using the triangular lattice structure instead of the square one. Further increase in this bandwidth is obtained when GaAs is used as the background dielectric material. Simulation of such systems verifies these predictions with an increase in Δ up to $\approx$ 137% when triangular lattice is used and to $\approx$218% when GaAs is used with triangular lattice. This increase in bandwidth requires more length of the waveguide and leads to some dispersion in the group-velocity of the propagating pulse. In spite of these pitfalls, using the triangular lattice and GaAs represents a two steps optimization of the dynamic model.

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