Spatially-Variant Photonic Crystals and Possible Applications

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***Abstract*—Spatially-variant photonic crystals (SVPCs) are a new concept in photonics that provide new optical properties and an extraordinary means for multiplexing functions and incorporating bio-inspired randomness and materials. In the present work, planar SVPCs based on self-collimation are investigated.**

***Keywords*—photonic crystals, spatially-variant, nanophotonics**

I. Introduction

Photonic crystals are periodic structures that control light in ways that are analogous to how electrons are controlled in semiconductors [1]. They can exhibit optical band gaps which have been used to inhibit spontaneous emission [2], form all-dielectric mirrors [1][3][4], form waveguides [5][6], and more [7]. They can also exhibit useful dispersion properties that have been used for superprisms [8], negative refraction [9], dispersion compensation [10], and more [11]. The present research is mostly based on the self-collimation effect where light is forced to propagate along an axis of the lattice regardless of angle of incidence [12]. Inside of self-collimating photonic crystals, beams do not diverge and remain collimated indefinitely. Self-collimation has been used for interferometry [13], beam splitters [14], ring-resonator filters [15], and more.

In recent years, a technique was presented that could bend, twist, and otherwise spatially-vary the geometric properties of a periodic structure while minimizing unintentional deformations to the unit cells [16][17]. For optical and electromagnetic applications, it is critical to avoid unintentional deformations as these weaken or erase the properties of the photonic crystal. In the present work, spatially-variant photonic crystals (SVPCs) based on self-collimation have been developed and explored as a new mechanism for controlling light [18]. This prior research has shown that SVPCs can exhibit extraordinary control and manipulate light very abruptly.

II. Generating Spatially-Variant Lattices

A. Spatially-Variant Planar Gratings

A planar grating is described by its average refractive index n_{avg}, index contrast Δn, and grating vector $\vec{K}$ according to Eq. (1), where $\vec{r}$ is position.

$$n(\vec{r}) = n_{\text{avg}} + \Delta n \cos\left(\vec{K} \cdot \vec{r}\right) \quad (1)$$

The grating vector $\vec{K}$ defines the period and orientation of the grating. When the grating is spatially varied, the grating vector becomes a function of position and Eq. (1) fails to properly calculate the grating. To mitigate this, an intermediate parameter is introduced called the grating phase Φ. The grating phase is related to the grating vector through Eq. (2), which is the key equation behind spatial variance.

$$\nabla\Phi(\vec{r}) = \vec{K}(\vec{r}) \quad (2)$$

After solving Eq. (2) for the grating phase, the planar grating is calculated according to

$$n(\vec{r}) = n_{\text{avg}}(\vec{r}) + \Delta n(\vec{r}) \cos\left[\Phi(\vec{r})\right] \quad (3)$$

In this equation, the average refractive index and index contrast parameters have also been made a function of position. In this manner, all of the attributes of a planar grating can be spatially varied.

An example of a spatially-variant planar grating is shown in Fig. 1. The $\vec{K}$ function, illustrated in Fig. 1(a), contains a region in the shape of the state of Florida. Inside this region, the grating period is 2.0 and the orientation of the grating is 45° with respect to the *x*-axis. Outside of this region, the grating period is set to 1.0 and the orientation is perpendicular to the *x*-axis. The analog grating computed using this $\vec{K}$ function is shown in Fig. 1(b). Note that the grating remains smooth and continuous even though the grating vector $\vec{K}$ changes rather abruptly inside of the Florida region.

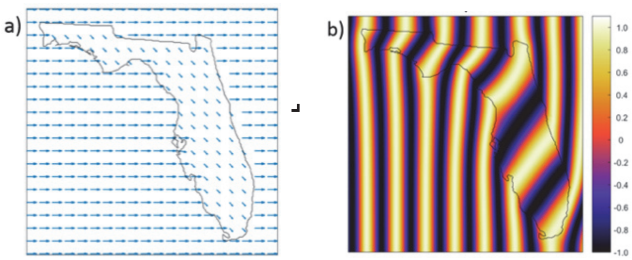

Fig. 1: a) Example $\vec{K}$ function. b) Spatially-variant grating computed using the given $\vec{K}$ function.

B. *Spatially-Variant Lattices*

To spatially vary a lattice, the lattice is first decomposed into a set of planar gratings, each of the planar gratings are individually spatially varied, and the results are added to form the overall lattice. To calculate the set of planar gratings, the unit cell is expanded into a Fourier series along its reciprocal lattice vectors $\vec{T}_1$, $\vec{T}_2$, and $\vec{T}_3$ according to Eq. (4) and (5).

$$n(\vec{r}) = \sum_{p,q,r} a_{p,q,r} e^{j\left(p\vec{T}_1 + q\vec{T}_2 + r\vec{T}_3\right)\bullet\vec{r}} \tag{4}$$

$$a_{p,q,r} = \frac{1}{V}\iiint_V n(\vec{r}) e^{-j\left(p\vec{T}_1 + q\vec{T}_2 + r\vec{T}_3\right)\bullet\vec{r}} dV \tag{5}$$

The Fourier coefficients $a_{p,q,r}$ are complex numbers that quantify the amplitude and offset of each of the planar grating components. V is the volume of the unit cell. The total range of possible things to spatially vary becomes apparent when the Fourier series parameters are also made functions of position. When this is done, Eq. (4) becomes

$$n(\vec{r}) = \sum_{p,q,r} a_{p,q,r}(\vec{r}) e^{j\left[p\vec{T}_1(\vec{r}) + q\vec{T}_2(\vec{r}) + r\vec{T}_3(\vec{r})\right]\bullet\vec{r}} \tag{6}$$

Using Eq. (6) it becomes possible to spatially vary all of the attributes while still generating an overall lattice that is smooth, continuous, defect-free and that minimizes unintentional deformations to the unit cells. Attributes that can be spatially varied include the orientation of the unit cells, lattice spacing, lattice symmetry, fill factor, pattern within the unit cell, and more. In fact, Eq. (6) ensures all of these can be spatially varied at the same time and all in unique patterns.

The ability to spatially vary multiple attributes of a lattice simultaneously is demonstrated in Fig. 2. In this example, the spatially varied attributes are: lattice spacing, orientation of the unit cells, and fill factor. Each of these inputs are spatially varied in a unique way and the overall lattice remains smooth. Continuous, and defect free as expected.

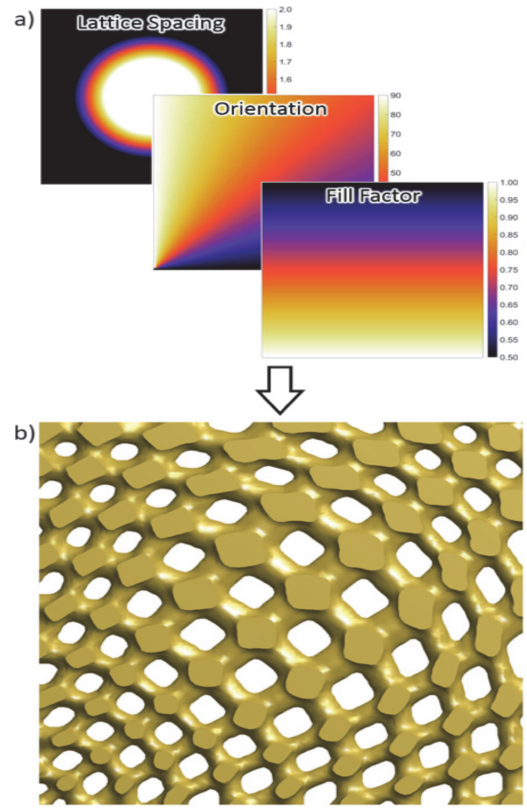

Fig. 2: a) Inputs to spatially vary the lattice. b) Lattice with three parameters spatially varied simultaneously and in unique patterns.

C. *Incorporating Randomness*

Profound perfection can be found in nature's imperfections. This is particularly true of periodic structures observed in nature, which leverage randomness to provide more omnidirectional behavior [19], greater immunity to damage and deformations, identification of friend/foe, and likely many things we have yet to discover. In electromagnetic and photonic systems, randomness has been shown to provide wide band gaps [19] and to suppress side lobes of array antennas and frequency selective surfaces [20]. Random scatter has also been used for optical cloaking [21].

The algorithm described above provides an extraordinary means to incorporate randomness into SVPCs. It is possible to introduce any level of randomness to each attribute of the lattice independently while still generating an overall lattice that is smooth, continuous, and free of unintentional defects. Fig. 3 shows an example of this. The lattice in Fig. 3(a) has a 90° bend and is otherwise uniform. In Fig. 3(b), this same structure is presented, but with some randomness incorporated into the orientation, period, and fill factor maps. As can be seen, the lattice is aperiodic, randomized, and yet remains smooth, continuous, and free of defects.

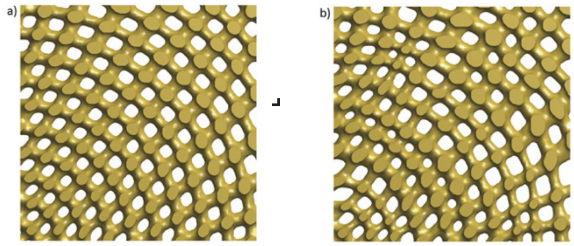

Fig. 3: a) Uniform lattice with a 90° bend. b) Same structure but with some randomness incorporated into the orientation, period, and fill factor parameters.

III. Implementation and Possible Applications

In this section we summarize our work [22] and present our results for planar SVLs with high and low Δn structures[1]. We then present an approach to transform our algorithms to HPC platforms.

A. *Current Research and Results*

Fig. 4 shows the steps we took to simulate the propagation of an EM wave impinging on a SVL structure.

STEP 1: Define the unit cell structure. The unit cell, outlined by the dashed lines, is made of silicon ($n = 3.5$), has a lattice spacing of a, and consists of sheets with thickness t and rods of radius r. We analyzed different variants of this structure, changing the values of n, t, and r each time. We also looked at unit cells with different geometries, including triangles, circles, squares, and random geometries, but found this structure to be the best for self-collimation.

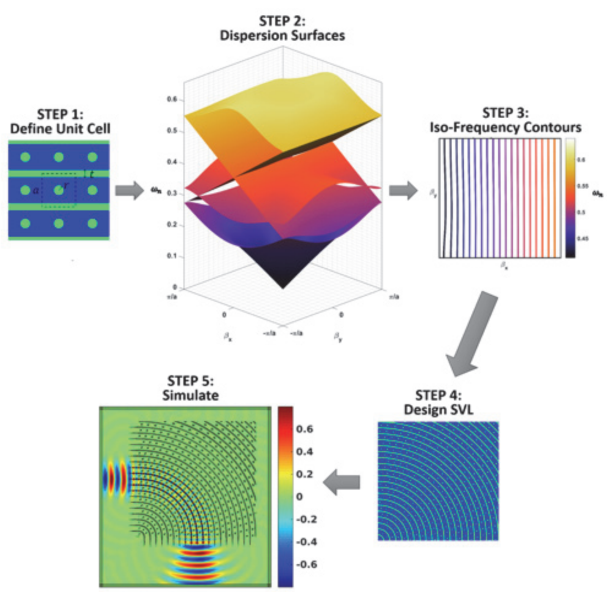

Fig. 4: Design workflow for self-collimating photonic crystals.

STEP 2: Analyze the unit cell using the plane wave expansion method (PWEM). Through PWEM, we calculate the dispersion surfaces which describe the spatial dispersion of the lattice at a specific frequency.

STEP 3: Generate the iso-frequency contours (IFC) by finding the intersection between constant frequency planes and the dispersion surfaces. Self-collimation occurs where the IFC is flat over some span of wave vectors β and over some band of frequencies ω_n.

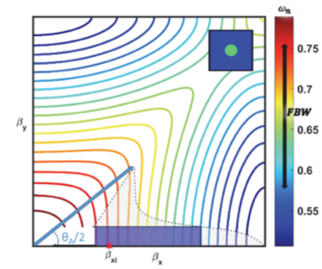

Fig. 5: Performance metrics for self-collimation.

STEP 4: Optimize the unit cell for self-collimation using the following metrics [23]: strength metric (S), fractional bandwidth (FBW), and acceptance angle (θ_A), as shown in Fig. 5. The figure of merit is calculated directly from these performance metrics: $FOM = \sqrt[3]{S * FBW * \theta_A}$.

STEP 5: Simulate an EM wave impinging on the structure using the finite-difference frequency-domain (FDFD) method. For this work, we demonstrate the self-collimation effect by varying the orientation of the unit cells in the lattice to form a 90 degree bend as shown in Fig. 6(b). Simulations were performed for both low and high Δn cases. The structure is the same in both cases, but with slightly different dimensions. The high Δn lattice, with a higher FOM, performs better for self-collimation. In the FDFD simulation, this is conveyed through less scattering at the input and output faces of the lattice, as well as along the bend.

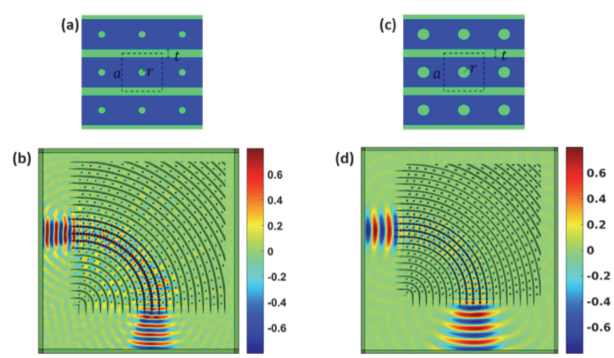

Fig. 6: Optimized unit cells for self-collimation. (a) Planar, low Δn structure. (b) Beam propagation through the SVL with low Δn. (c) Planar, high Δn structure. (d) Beam propagation through the SVL with high Δn.

[1] Δn is the refractive index contrast and is determined by getting the absolute difference between the refractive index of the material that the unit cell is made of and the material surrounding it. $\Delta n > 1$ is considered high and $\Delta n \leq 1$is considered low.

B. *Possible Applications and Way Forward*

The simulations provide insights into the self-collimation phenomenon that will enable new device functionality over a broad spectral range. Harnessing these qualities in photonic crystals can provide advanced features in a variety of applications: decreased size and cost of scene projection systems, improved performance collimators and collecting optics, broadband optics with very wide acceptance angles, improved emitter and detector efficiencies, compressive sensing applications, radical system miniaturization through multiplexing and light couplers for integrated photonics.

Current computational limitations hinder the design of larger scale, higher complexity devices[2]. Simulation of planar 20×20 and 100×100 lattices require approximately 30 minutes and 24 hours respectively to execute using the current MATLAB scripting. The corresponding memory footprint for the larger lattice is greater than 20 GB. Consequently, large lattices with a substantial number of parametric variations (unit cell shapes, materials, wavelengths, incidence angles, etc.) are prohibitive. Increasing the structural dimensions of the photonic crystals to two or three will be practically impossible.

In order to enhance the quality and size of simulations, the current MATLAB script used is undergoing migration to C/C++ using optimized linear algebra libraries for implementation on high performance computing (HPC) platforms. Further improvements to efficiency are expected as multiple simultaneous simulation configurations will be performed on multiple cores or a complex configuration can be executed using multiple cores. All modifications for HPC will also preserve the heterogeneous system execution capability utilizing both CPUs and GPUs.

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REFERENCES

[1] Joannopoulos, John D., et al. Photonic crystals: molding the flow of light. Princeton university press, 2011.

[2] Yablonovitch, Eli. "Inhibited spontaneous emission in solid-state physics and electronics." Physical review letters 58.20 (1987): 2059.

[3] John, Sajeev. "Strong localization of photons in certain disordered dielectric superlattices." Physical review letters 58.23 (1987): 2486.

[4] Bruyant, A., et al. "All-silicon omnidirectional mirrors based on one-dimensional photonic crystals." Applied Physics Letters 82.19 (2003): 3227-3229.

[5] Mekis, Attila, et al. "High transmission through sharp bends in photonic crystal waveguides." Physical Review Letters 77.18 (1996): 3787.

[6] Russell, Philip St J. "Photonic-crystal fibers." Journal of lightwave technology 24.12 (2006): 4729-4749.

[7] Yasumoto, Kiyotoshi, ed. Electromagnetic theory and applications for photonic crystals. CRC press, 2005.

[8] Kosaka, Hideo, et al. "Superprism phenomena in photonic crystals." Physical review B 58.16 (1998): R10096.

[9] Cubukcu, Ertugrul, et al. "Electromagnetic waves: Negative refraction by photonic crystals." Nature 423.6940 (2003): 604.

[10] Shen, L. P., et al. "Design and optimization of photonic crystal fibers for broad-band dispersion compensation." IEEE photonics technology letters 15.4 (2003): 540-542.

[11] Gralak, Boris, Stefan Enoch, and Gérard Tayeb. "Anomalous refractive properties of photonic crystals." JOSA A 17.6 (2000): 1012-1020.

[12] Kosaka, Hideo, et al. "Self-collimating phenomena in photonic crystals." Applied Physics Letters 74.9 (1999): 1212-1214.

[13] Zhao, Deyin, et al. "Photonic crystal Mach-Zehnder interferometer based on self-collimation." Applied Physics Letters 90.23 (2007): 231114.

[14] Yu, Xiaofang, and Shanhui Fan. "Bends and splitters for self-collimated beams in photonic crystals." Applied Physics Letters 83.16 (2003): 3251-3253.

[15] Chen, Xiyao, et al. "Polarization-independent drop filters based on photonic crystal self-collimation ring resonators." Optics express 17.22 (2009): 19808-19813.

[16] Rumpf, Raymond C., and Javier Pazos. "Synthesis of spatially variant lattices." Optics express 20.14 (2012): 15263-15274.

[17] Rumpf, Raymond C., et al. "Spatially variant periodic structures in electromagnetics." Phil. Trans. R. Soc. A 373.2049 (2015): 20140359.

[18] Digaum, Jennefir L., et al. "Tight control of light beams in photonic crystals with spatially-variant lattice orientation." Optics express 22.21 (2014): 25788-25804.

[19] David, Sylvain, A. Chelnikov, and J-M. Lourtioz. "Isotropic photonic structures: Archimedean-like tilings and quasi-crystals." IEEE Journal of Quantum Electronics 37.11 (2001): 1427-1434.

[20] Kim, Y., and D. L. Jaggard. "The fractal random array." Proceedings of the IEEE 74.9 (1986): 1278-1280.

[21] Schittny, Robert, et al. "Invisibility cloaking in a diffusive light scattering medium." Science (2014): 1254524.

[22] Noel P. Martinez, Jimmy E. Touma, "Design of Photonic Crystals for Biologically Inspired Systems", AFRL Scholars Porogram (2017).

[23] R.C. Rumpf, and J. Pazos, "Optimization of planar self-collimating photonic crystals," J. Opt. Soc. Am. A, Vol. 30, No. 7, pp. 1297-1304 (2013)

[2] The system is a dual quad core Xeon processors @ 3.47 GHz and 96GB RAM.