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Bio-Inspired Spatially Variant Photonic Crystals for Beam-Steering Applications

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Abstract

The self-collimation of light through Photonic Crystals (PCs) due to their optical properties and through a special geometric structure offers a new form of beam steering with highly optical control capabilities for a range of different applications. The objective of this work is to understand self-collimation and bending of light beams through Spatially Variant Photonic Crystals (SVPCs) made from dielectric materials such as silicon dioxide as well as common polymers used in three-dimensional printing like SU-8. These PCs can be used for optical communications, multiplexing, and beam-tuning devices for light detection and ranging applications. In this paper we show the optical properties and potential applications of two different SVPC designs that can control light through a 90-degree bend and optical logic gates. These two-dimensional SVPC designs were optimized for operation in the near-infrared range of approximately 800-1000 nm for the 90-degree bend and 700-100nm for the optical logic gate. These SVPCs were shown to provide high transmission through desired regions with low reflection and absorption of light to prove the potential benefits of these structures for future optical systems.

Introduction

Photonic Crystals (PCs) are periodic nanostructures designed to affect the motion of photons in the same way that the periodic potential in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands [1]. Spatially Variant Photonic Crystals (SVPCs) have been studied in the past and designed using materials that have a low-refractive index; they have shown their capability to adiabatically control light beams with high polarization selectivity [2] [3]. Two different polarizations can be considered when looking at the optical applications and functions of different devices such as PCs. In p-polarization (Transverse Magnetic–TM), the electric field is parallel to the plane of incidence, while in s-polarization (Transverse Electric–TE), the electric field is perpendicular to the plane of incidence. Optical devices can be designed and tailored to manipulate these different polarizations of light through their geometry and properties such as the refractive index and extinction coefficient. PCs and metamaterials exhibit dispersion properties that have been used for super prism, negative refraction, and dispersion compensation [1] [4]. In order to bend a beam of light, Spatially Variant Lattices (SVL) can be created by decomposing the lattice into a set of planar gratings. Each of these planar gratings are spatially varied individually. As a result, the entire geometry has a uniform variance [1] [5] [6], and the unit cell of the structure is expanded into a Fourier series along its reciprocal lattice vectors.

There are many different classifications and types of PCs. Each PC has different advantages and disadvantages over the others in their ease of fabrication and their applications. In order to create a structure that would allow us to finely tune the collimation and transmission of light in the near-infrared (IR) wavelength, a target wavelength for free-space optical applications, a PC based on an SVL was selected. This structure allows for self-collimation of the light beam through the structure by a band gap control mechanism, preventing the need for a waveguide when bending light since all bending of light is a result of the SVL itself. The SVL design took inspiration from PC structures found in nature, most notably in butterfly wings. We designed and simulated two-dimensional (2D) PCs in the near-IR wavelength using Finite Difference Time Domain (FDTD) simulations for two different design applications with a range of low-refractive index materials. The design for controlling light through a 90-degree bend is shown in Figure 1 (a) and the design for an OR logic gate is shown in Figure 1 (b).

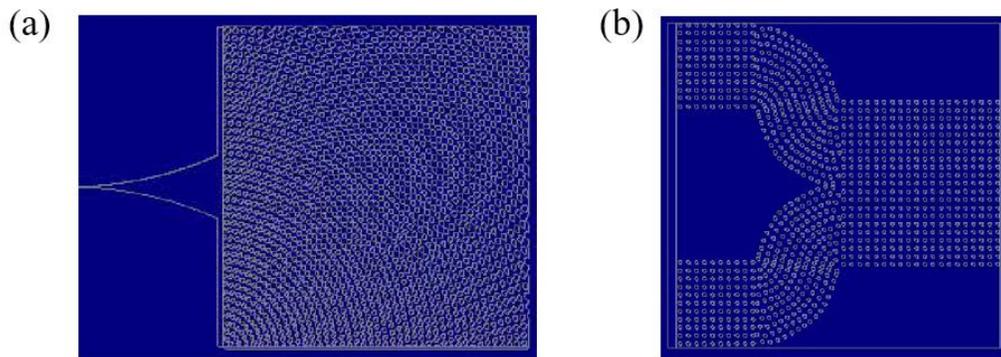


Figure 1: 2D SVPC models for (a) 90-degree bend and (b) simplified optical logic gate, i.e., OR gate. Models were developed through a combination of MATLAB and CAD software in SolidWorks and Lumerical.

The transmission, reflection, and absorption results from the simulation of these structures showed the optimal operational wavelengths for these designs as well as their merit for each

application. While SVPCs have been shown to be capable of self-collimation and beam-steering applications [1] [7], this work is unique in that it has been applied to the near-IR range. This unique application in the near-IR range allows for new applications. Previously, this team had shown the ability of SVPCs composed of Indium Tin Oxide (ITO) to control light through a 90-degree bend [2]. These ideas are now expanded to additional materials and applications. Applying the properties and functions discussed in this paper to further applications such as optical logic gates or multiplexers/demultiplexers is also a new innovation that can be improved upon and implemented in future work. Current logic gates work through electrical systems, but applying PCs to serve as logic gates in the near-IR range is a unique innovation that could greatly improve the speed and capacity of logic gates in the future.

Methods

Development of PCs and spatial variation. After investigating different geometric structures of SVPCs, the model based on a varying lattice proved to be the ideal structure for our applications in its ability to be fabricated with a quality design and be tuned for different frequencies. In this work, a combination of MATLAB and SolidWorks was used to generate the structures based on various equations for lattice structures and lattice constants for the selected materials. The following equations were used to generate the unit cell parameters and accompanying lattice structures:

$$K = K_x\hat{X} + K_y\hat{Y} + K_z\hat{Z}; K_x = \frac{2\pi p}{\Lambda_x}; K_y = \frac{2\pi q}{\Lambda_y}; K_z = \frac{2\pi r}{\Lambda_z} \quad (1)$$

where K is the grating vector of the lattice; K_x, K_y, K_z is the grating vectors for $x, y,$ and z directions; $p, q,$ and r are integers; and Λ_x, Λ_y and Λ_z are the grating periods for each direction. The lattice constant determines the fill fraction of the SVL. The fill fraction is given by Equation 2 as follows:

$$Ff = \frac{\frac{4}{3}\pi \times (d_{e_1}^3 \times t_{e_1} + d_{e_2}^3 \times t_{e_2})}{a} \quad (2)$$

where subscripts e_1 and e_2 represent the first and second elements in the compound, respectively; Ff is the fill fraction; the value for a for each element is the lattice constant; the value for t is the number of that atom in the molecule; and d is the atomic radius. To generate the model for simulation, d_{e_1} and d_{e_2} were the atomic radii of the two elements in our models.

In order to control the bending of light, spatial variation must be introduced into the lattice; this can be achieved by decomposing the lattice into a set of planar gratings that are individually spatially varied, allowing the entire geometry to have uniform variance [1]. The unit cell of the structure is expanded into a Fourier series along its reciprocal lattice vectors $T_1, T_2,$ and T_3 that can be expressed as:

$$n(r) = \sum_{p,q,r} a_{p,q,r} e^{j(pT_1+qT_2+rT_3)r} \quad (3)$$

where:

$$a_{p,q,r} = \frac{1}{V} \iiint n(r) e^{j(pT_1(r)+qT_2(r)+rT_3(r))r} dV. \quad (4)$$

The Fourier coefficients $a_{p,q,r}$ are complex numbers that quantify the amplitude and offset of each of the planar grating components [3] [6], V is the volume of the unit cell, r is the position vector, and $n(r)$ is the refractive index as a function of position. The total range of possible things to spatially vary becomes apparent when the Fourier series parameters are also made functions of the vector position, so Equation 3 can be written in a vector form as:

$$n(r) = \sum_{p,q,r} a_{p,q,r}(r) e^{j(pT_1+qT_2+rT_3) \cdot r}. \quad (5)$$

Using Equation 5, it is possible to spatially vary all of the attributes, e.g., lattice spacing, orientation of the unit cells, and fill factors, while still generating an overall lattice that is smooth, continuous, and defect free and that minimizes unintentional deformations to the unit cells [8] [4]. Once these 2D models are generated, they are loaded into 3D FDTD for simulation. In order to make three-dimensional (3D) PC structures, the 2D slabs can be assembled and stacked on top of one another. The buildup from a single unit cell of a PC to a 2D and 3D model is represented in Figure 2. The single unit cell is shown in Figure 2 (a), the 2D slab is shown in Figure 2 (b), and the full 3D model is shown in Figure 2 (c).

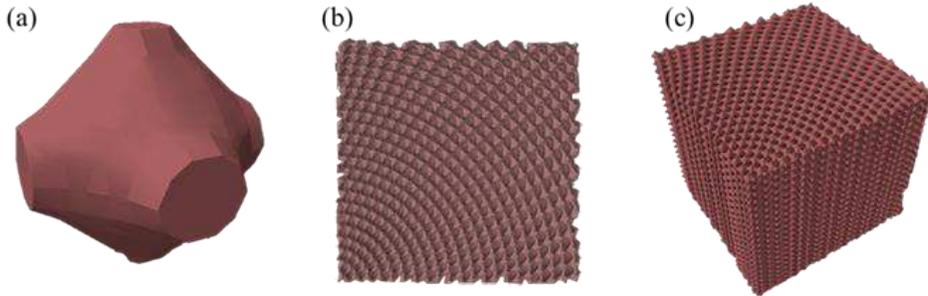


Figure 2: Models for buildup of PC structures. Models were generated for (a) Unit cell, (b) 2D slab, and (c) 3D assembly of SVPC structures.

These SVPC models can be used for each type of simulation. The unit cell can be tested to investigate self-collimation properties such as Iso-Frequency Contours (IFCs) discussed later in this paper. 2D slabs and 3D assemblies can be simulated in order to approximate how the structure will function in specific applications. In this paper, we outline our approach for the simulation of 2D PC structures.

Refractive index investigation. In order to control light in the near-IR region, low-refractive index materials such as Silicon Dioxide (SiO_2) and the polymer SU-8 are ideal for these applications. These materials were researched to find the refractive indices and extinction coefficients. As a negative epoxy-based photoresist, SU-8 is an ideal material for lithography fabrication. Its refractive index can be tailored to a range of different wavelengths based on the speed with which it is made and the thickness of the material [9]. Both SiO_2 and SU-8 have a constant extinction coefficient of zero. Since the extinction coefficient was not a factor for our applications in the near-IR range, we focused on the refractive index. SiO_2 has an approximately constant value of 1.45, and the polymer SU-8 has a constant value of around 1.56 in our area of

interest. These values were used in the simulation to determine which material was best suited for our two SVPC applications.

Anti-reflection coatings. The difference in the refractive index between the material of interest and the environment, e.g., air, can cause high reflection at the interface of the PC. In order to reduce losses due to reflection, Anti-Reflection Coatings (ARCs) were introduced to help ease the light into the structure. ARCs are made up of one or more thin layers placed on the interface of the structure [10] with a refractive index found using Equation 6:

$$n_{ARC} = \sqrt{n_1 n_2}. \quad (6)$$

The width, or thickness, of the ARC is related to the wavelength of interest (λ) of the applied incident beam as shown in Equation 7:

$$d = \frac{1}{4}\lambda. \quad (7)$$

Using Equations 6 and 7, we can generate an ARC with a refractive index between the two materials that would allow the beam to be eased into the structure and reduce the amount of loss from reflection at the input interface of the SVPC in 1D, 2D, and 3D PCs [11]. For practical applications and fabrication where a single structure may be used for multiple wavelengths, the thickness can be selected for an average wavelength or the most common wavelength used in the system.

A few different geometries were considered for these ARCs in the various applications. The simplest form, a rectangular structure, was used for the logic gate applications that could allow multiple positions or incident angles to be used. In order to optimize the transmission for the 90-degree bend, a tapered cone was used as the ARC structure to give a specific point of entry to guide the beam into the SVPC structure. Both of these ARCs were able to reduce the amount of reflection at the input and help guide the various wavelengths of light into the respective structures and improve the transmission results. While more complex waveguides such as the tapered cone used for the 90-degree bend provide the greatest improvement in transmission, their complexity in both fabrication and implementation may limit its potential applications.

Numerical modeling with the 2D FDTD method. To study the self-collimation and transmission of multiple SVPC structures for different applications, the FDTD method can be used in commercial software such as Lumerical. 2D structures were developed through a combination of MATLAB and Computer Aided Design (CAD) software in SolidWorks and Lumerical. Using unit cells of these lattice structures, we could develop a model to observe its band gaps and predict its ability to maintain self-collimation of different wavelengths of light. These results helped us to create simulation models to find the transmission and reflection characteristics for different wavelengths of each application. Starting with 2D simulations is reasonable as 3D simulations will be too time-intensive for preliminary analysis.

Results and discussion

PC band gap analysis. To show the ability of SVPCs in applications for beam steering and logic gates, we can take advantage of band gaps and self-collimation of PC structures. PCs can affect

the motion of photons, so we can tune the light in a desired direction through a 90-degree bend. The ability to distort or bend the light is dependent on the photonic band gap of the structure and the density of d-vectors as a function of angular directions. The photonic band gap is a range of frequencies in which certain wavelengths of light are blocked by a structure [12]. Photons of wavelengths lying in the photonic band gap cannot propagate through the structure because they do not match the frequency needed to propagate. The band gap for SiO₂ is shown in Figure 3 (a). Taking advantage of this property, the flow of light can be controlled by prohibiting or allowing light to flow in certain directions in k-space. This flow of light is specifically controlled through tailoring the geometric structure and material of the SVPC to manipulate the band gap. The ability of the SVPC to force light in specific directions as a result of the density of k-vectors enables self-collimation throughout the structure [12]. Moreover, by adiabatically introducing a rotation to the PC, we can manipulate the direction of the flow of light without leaving the autocollimation regime. This innovation will make it possible to replace waveguides in the future by this type of self-guiding.

The capability of self-collimation can be shown through Iso-Frequency Contours (IFCs); these contours provide insight into understanding key optical concepts such as negative refraction, super collimation, and super lensing. The angular distribution of the scattered photons leads to the formation of IFCs in the far field. Light passes through perpendicular to the contours of the IFC. The distribution of k-vectors in the images in Figure 3 (b) and (c), show that as long as the light enters within that range, k-vectors will force light to travel in the same direction. By limiting the input angle, we can ensure that the light travels along the same path and remains collimated throughout the entire structure. Prior work has shown the promise of IFCs to show self-collimation at wavelengths in the microwave region. In this work, we expanded this application to the near-IR range and showed that IFCs can maintain self-collimation through our SVPC designs. Using 3D FDTD, we can focus on a single unit cell of our structure to find the band gap and IFCs for SiO₂ as shown in Figure 3.

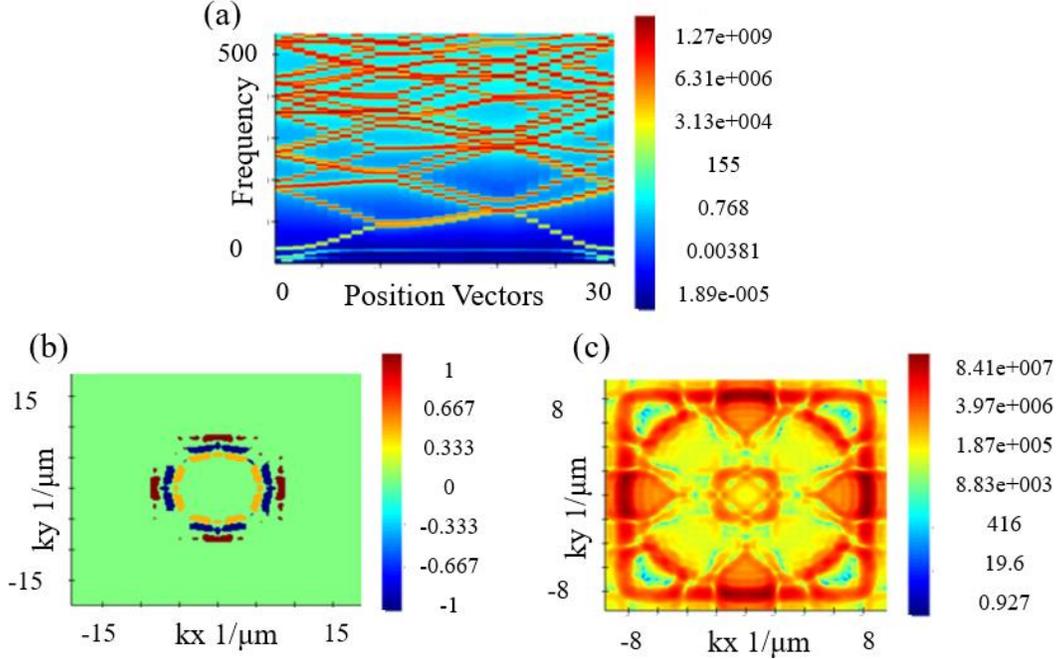


Figure 3: FDTD models of SiO₂ PC unit cell for (a) band structure, (b) IFC for multiple wavelengths, and (c) IFC at 1000 nm.

The results shown in Figure 3 allow us to predict how the PC will respond when subjected to a certain frequency. The vectors k_x and k_y denote the x and y components of the k -vector. In order to maintain self-collimation through our unit cell, the beam divergence angle must be kept below ± 14.03 degrees. The beam must have a constant value of -8 [$1/\mu\text{m}$] for k_x , while k_y can range between -2 and 2 [$1/\mu\text{m}$] because in this region the density of the k -vectors is the strongest. As long as these parameters are followed, self-collimation should be maintained throughout the structure. We can take advantage of these properties and design characteristics to develop SVPCs for specific applications in beam steering.

The 90-degree bend. Our first SVPC model was designed for beam-steering applications. Generally, bending light in an integrated structure requires the fabrication of waveguides, whereas multiple input beams would require multiple waveguides. Through self-collimation, it is possible to bend light without necessitating a guided wave geometry, significantly reducing the complexity of fabrication. Our design was modeled to maintain self-collimation of light in the near-IR range through a 90-degree bend. This model, shown in Figure 1 (a), was loaded into FDTD for simulation. Parameters were set to test a range of wavelengths from 600 to 1000 nm with monitors set at each face to find the absorption, reflection, and transmission through the different faces. This 2D model is shown in Figure 4 with (a) top and (b) isometric views.

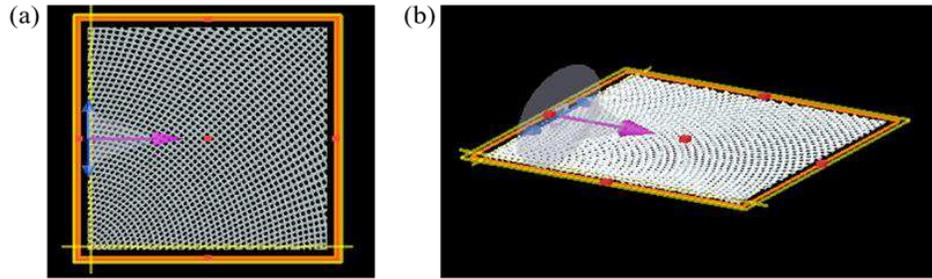


Figure 4: 2D SVL simulation: (a) Top view and (b) Isometric view. Blue arrows indicate the polarization of the beam, the purple arrow indicates the propagation direction of the input beam. Red dots indicate the center point of the structure and midpoints of the simulation border. The orange/yellow borders show the monitors for transmission and reflection.

Using this model, we were able to test two different materials: SiO₂ and SU-8. This testing gives a range of results that could fit different fabrication methods. Materials such as SiO₂ can be fabricated by etching into material substrates, while the polymer SU-8 could be used for more exact lithography and printing.

Numerical modeling and simulation. With this information in mind, we can generate our SVPC structures and perform FDTD simulations in Lumerical. A structure was generated and tested with each material from 800 to 1000 nm. Figure 5 shows that the SVPC structure for (a) SiO₂ and (b) SU-8. was able to keep the incident light self-collimated as it bent 90 degrees through the structure.

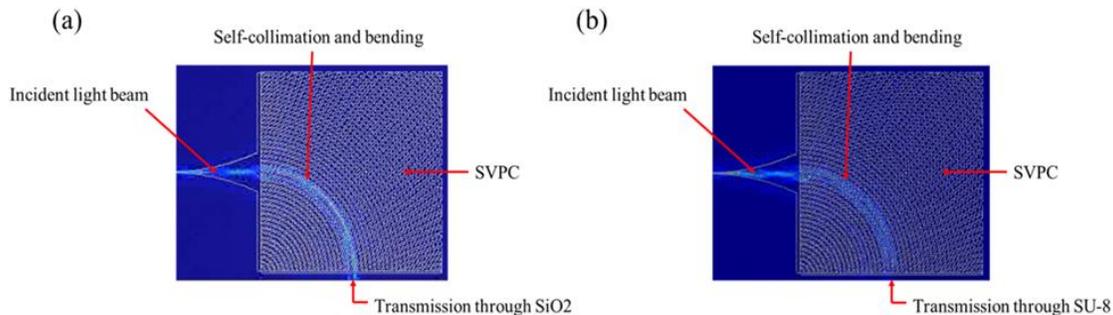


Figure 5: Simulation model for light passing through SVPC structure. Similar results were found for both (a) SiO₂ and (b) SU-8.

The light is shown to be slightly brighter for the SiO₂ model as it was able to achieve higher transmission due to a lower refractive index. Transmission and reflection data were calculated for every 10 nm for each structure. The results for transmission are shown in Figure 6.

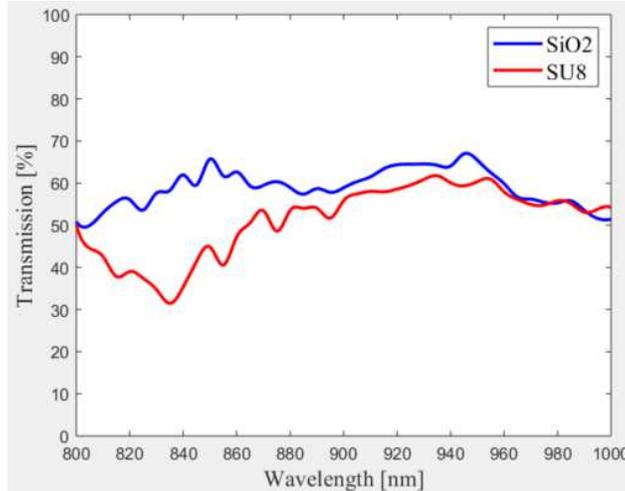


Figure 6: Transmission results (percentage) for SVPCs designed with SiO₂ and SU-8 in the near-IR region from 800-1000 nm using FDTD simulations in Lumerical.

This data allows us to better understand how our SVPCs may operate and which materials are best suited for beam-steering applications. These results show that SiO₂ is able to achieve significantly higher transmission than SU-8; this is a result of the difference in refractive index as SiO₂ has a much lower value of approximately 1.45 while SU-8 is higher at 1.56, respectively. The peak values for each material are presented in Table 1; please note that the summation of all transmission and reflection data is not exactly equal to 100% due to rounding the values.

Table 1: Peak transmission results (percentage) for SVPCs designed for the control of light through a 90-degree bend with SiO₂ and SU-8.

Material	Peak Wavelength [nm]	Bent Transmission [%]	Transmission through SVPC [%]	Transmission Deflected Upward [%]	Reflection [%]
SiO ₂	945	66.99	10.00	12.71	10.31
SU-8	935	61.76	12.28	11.07	14.88

Using these results, we can select which material is best suited for operation in specific wavelengths or understand how we can tune the PC to operate under different conditions.

Optical logic gate. The second SVPC model was designed for optical logic gates based on linear optics, specifically OR gates. The same principle of self-collimation allows the SVPC to direct two separate light beams along the same path in order to function as an OR gate (Figure 7); this can be done using two input beams of either the same or different wavelengths within the near-IR range. Essentially, when both teams are in the High state (on), the merged output exceeds the threshold for a logic high, while if either of them is in the Low state (off), the output drops below the threshold for a logic high. Implementing an SVPC that can direct light for this application through a geometric structure and a material's refractive index could allow these optical logic gates to be implemented into optical systems more often and more easily without the need of larger, heavier optical hardware. This model, shown in Figure 7 (b), was generated in FDTD using a similar method for spatial variation of unit cells for the 90-degree bend. As shown in the Figure 7

(a), an electronic logic OR gate is compared with an optical OR gate using a PC with nanocavity-enabled logic gates.

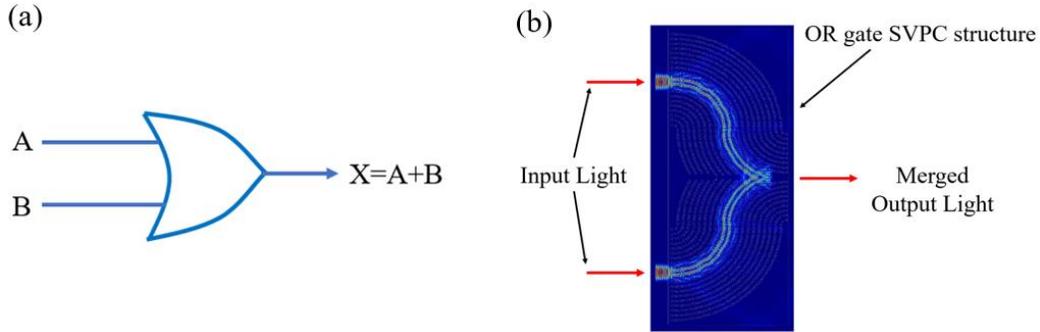


Figure 7: (a) Electronic OR gate; (b) 2D SVPC model for optical OR gates.

This structure should be able to maintain self-collimation as it guides two different beams from multiple inputs to a single output. Utilizing low-refractive index materials and the geometric structure will show the potential for the SVPC to function for applications with optical logic gates.

Numerical modeling and simulation. Using the model shown in Figure 7 (b), material properties were assigned and tested from 700 to 1000 nm. Input beams using these wavelengths were sent from two entry points as shown in Figure 7 (b) and used self-collimation to merge the light into a single output. While some optical logic gates function with input beams using different wavelengths, simulations were conducted where both beams used the same input wavelength. These and gate simulations were conducted using the same materials as our previous simulations: SiO₂ and SU-8. The results from these simulations are shown in Figure 8. This work will be expanded in the future to include the properties of other low-refractive index materials.

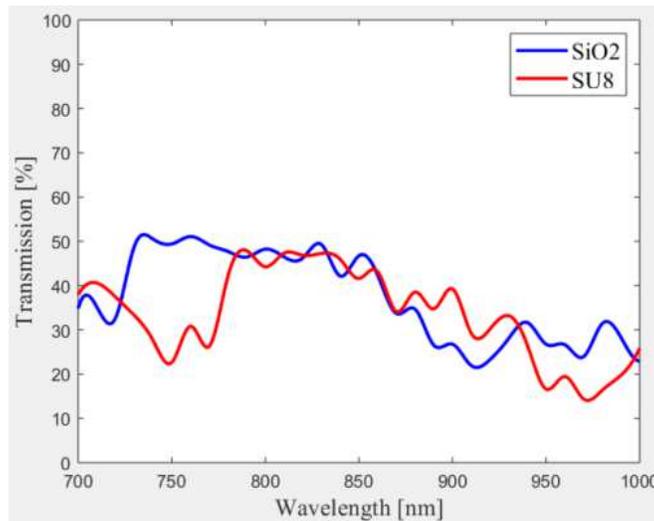


Figure 8: Transmission results for optical logic gate (OR gates) with two different low-refractive index materials. Results for SiO₂ and SU-8 are shown by the blue and red lines, respectively.

These results show that the highest transmission was achieved using SiO₂ at 760 nm with 51.1% of the input light collimating and merging into a single output. The transmission results for logic gates were not as consistent throughout the near-IR range as they were for the simpler 90-

degree bend application; this decrease in consistent transmission across the near-IR range is likely due to the multiple bends required to develop the OR gate structure. SiO₂ was able to achieve the highest overall transmission values as well as having a consistently higher value across a majority of the near-IR spectrum than SU-8. Similar to SiO₂, however, the values for SU-8 were also not as consistent as the values generated with our first model. Adjusting the hole size and spacing for the variation in the lattice could lead to more consistent, improved results. This work will be pursued in the future to show the added benefits of SVPCs for optical logic gates.

Another benefit of logic gates are the ability to control multiple dissimilar wavelengths at the same time. To show this ability, a simulation was run with one beam of incident light set to 750 nm and the second set to 850 nm as shown in Figure 9. The SVPC's ability to multiplex multiple inputs of dissimilar wavelengths into a single output makes it ideal for logic gate applications. This SVPC-based optical logic gate has advantages over waveguide-based logic gates in their ability to be designed to fit a wider range of wavelengths and the ability to utilize multiplexing/demultiplexing to operate with multiple inputs.

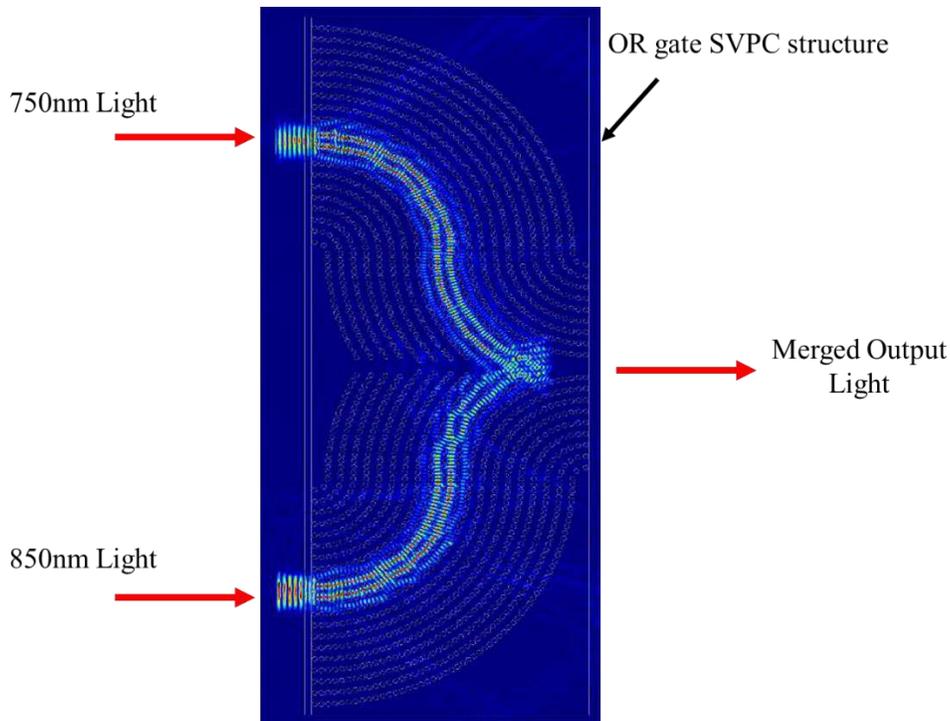


Figure 9: SiO₂ SVPC optical logic gate for two dissimilar wavelengths

This result shows that even with two dissimilar wavelengths, a single SVPC structure can be used to maintain self-collimation while directing and merging light together. The transmission and reflection values are shown in Table 2.

Table 2: Transmission and reflection results for SVPC optical logic gate with dissimilar wavelengths

Material	Wavelength [nm]	Bent Transmission [%]	Transmission through SVPC [%]	Reflection [%]
SiO ₂	750 and 850	50.31	17.31	32.39
SU-8	750 and 850	35.33	16.08	48.58

These results for dissimilar wavelengths show the potential benefits of this SVPC design. SiO₂ was significantly more successful than SU-8 with 50.31% transmission compared to 35.33%. This difference is likely due to the consistently higher results of SiO₂. Though SU-8 was able to achieve high results with similar wavelengths, these values were not as consistent as those for SiO₂. This means that SiO₂ could have a greater benefit for logic gate applications using dissimilar wavelengths.

Discussion

This work has shown the ability to design SVPCs for specific optical applications in the near-IR range. Using low-refractive index materials such as SiO₂ or SU-8, SVPCs can be designed based on SVLs in order to maintain self-collimation of light through sharp bends; this can be shown through slow variation and bends between individual unit cells and their respective IFCs in order to keep high transmission through these bends. These capabilities show promise for SVPCs in applications such as beam steering and logic gates. Through their geometric design and small weight, these structures continue to show their advantage over standard optical equipment and waveguides for the previously described applications. In the current work, initial models for these applications are being fabricated to verify our results with the experimental results and to begin moving towards implementation of SVPCs for new optical systems.

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Author Contributions

Rudra Gnawali, Imad Agha, and Jimmy Touma were responsible for the original research concept. Rudra and Andrew Volk performed the modeling and simulation of the SVPC structures. All other team members collaborated to organize work and write this paper.

Additional Information

Competing financial interests: The authors declare no competing financial interests.

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Figures

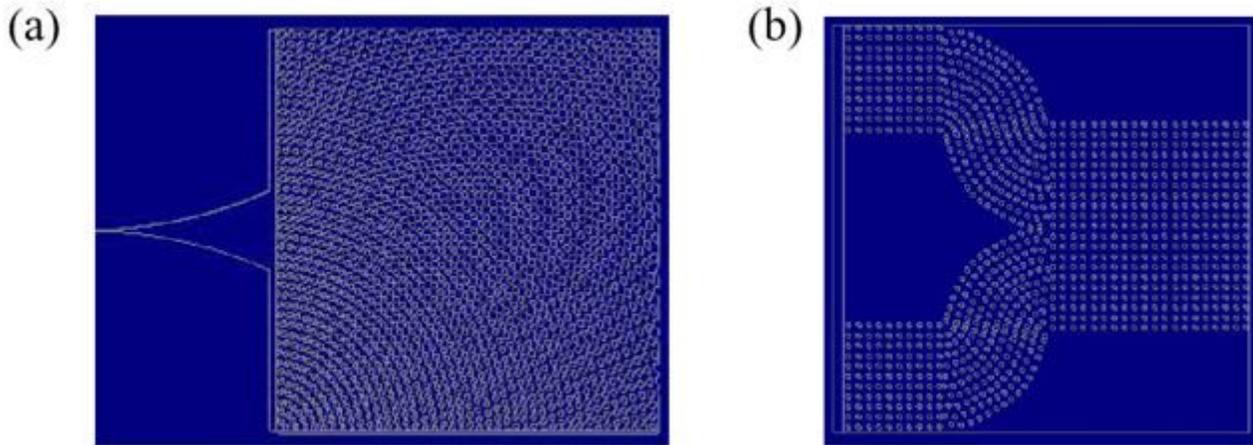


Figure 1

2D SVPC models for (a) 90-degree bend and (b) simplified optical logic gate, i.e., OR gate. Models were developed through a combination of MATLAB and CAD software in SolidWorks and Lumerical.

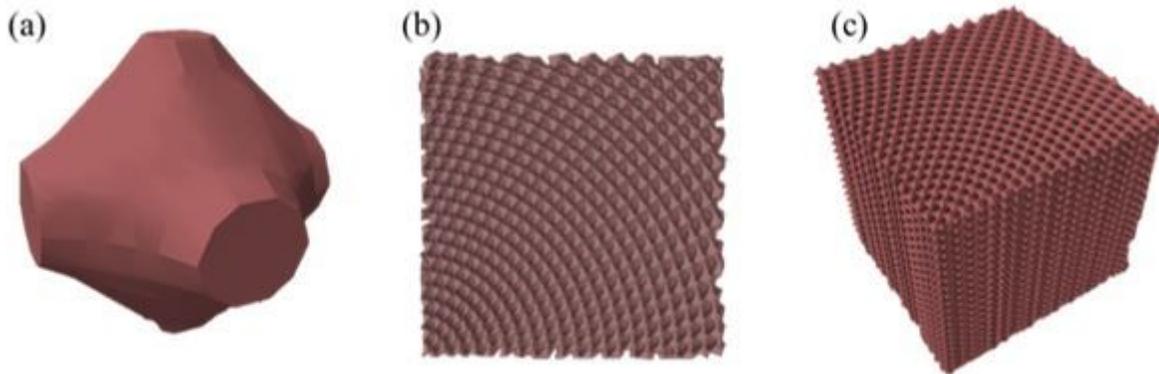


Figure 2

Models for buildup of PC structures. Models were generated for (a) Unit cell, (b) 2D slab, and (c) 3D assembly of SVPC structures.

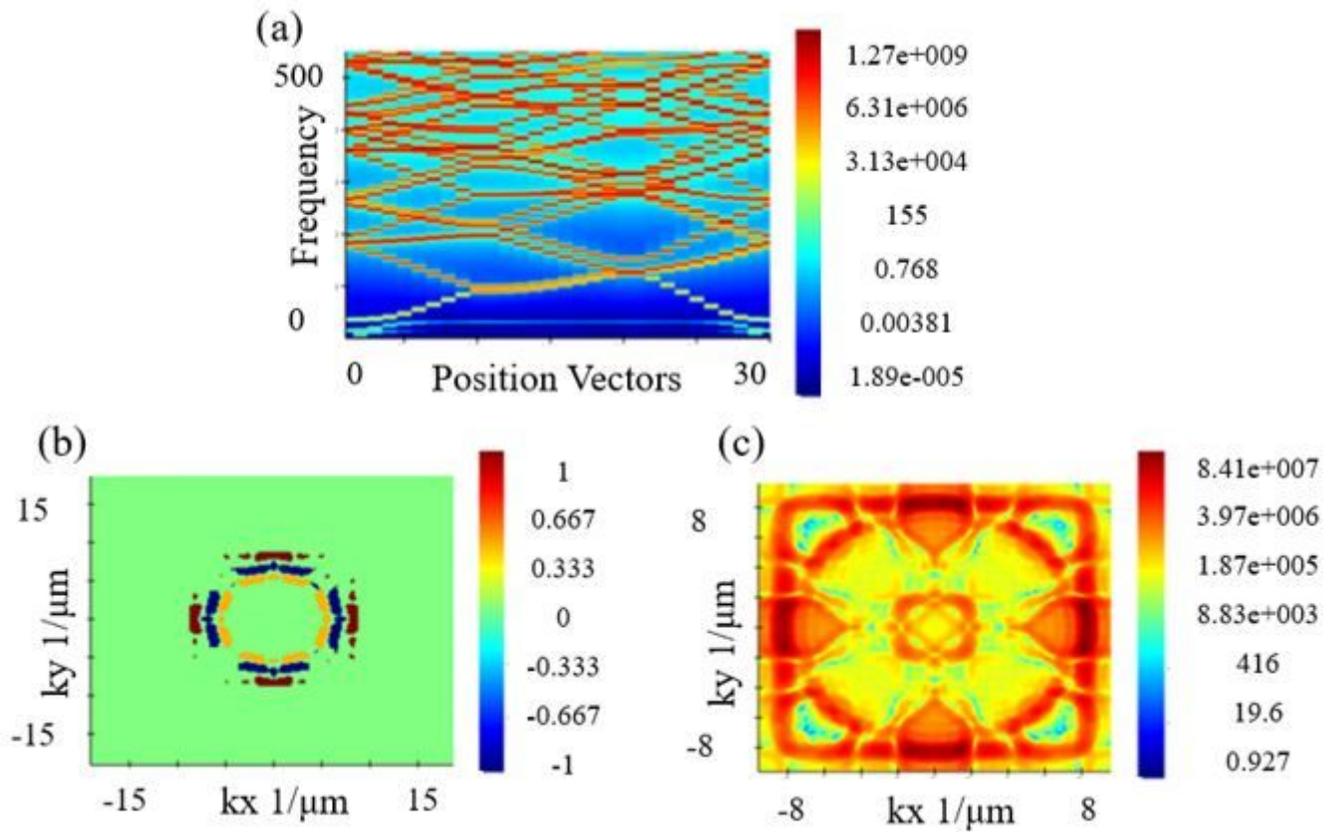


Figure 3

FDTD models of SiO₂ PC unit cell for (a) band structure, (b) IFC for multiple wavelengths, and (c) IFC at 1000 nm.

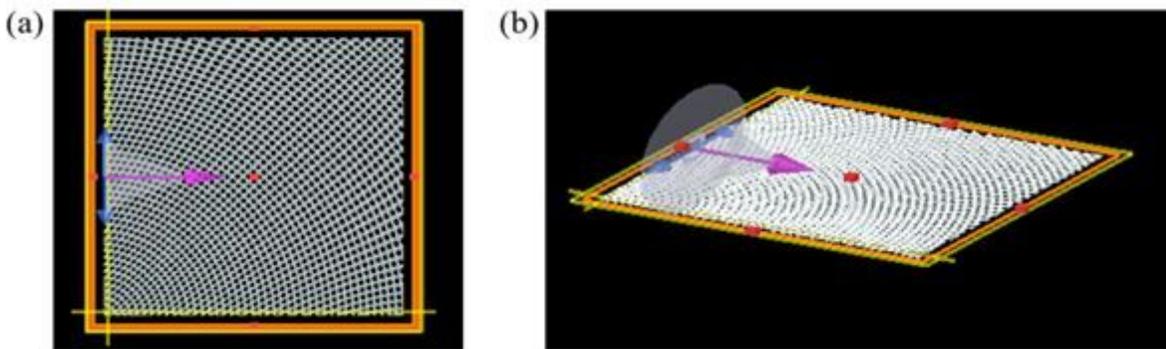


Figure 4

2D SVL simulation: (a) Top view and (b) Isometric view. Blue arrows indicate the polarization of the beam, the purple arrow indicates the propagation direction of the input beam. Red dots indicate the center point of the structure and midpoints of the simulation border. The orange/yellow borders show the monitors for transmission and reflection.

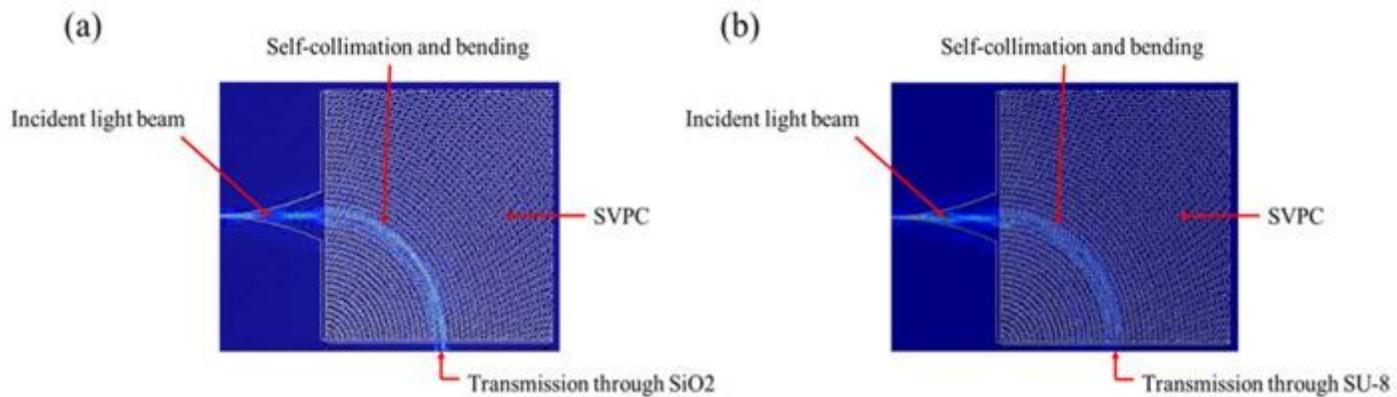


Figure 5

Simulation model for light passing through SVPC structure. Similar results were found for both (a) SiO₂ and (b) SU-8.

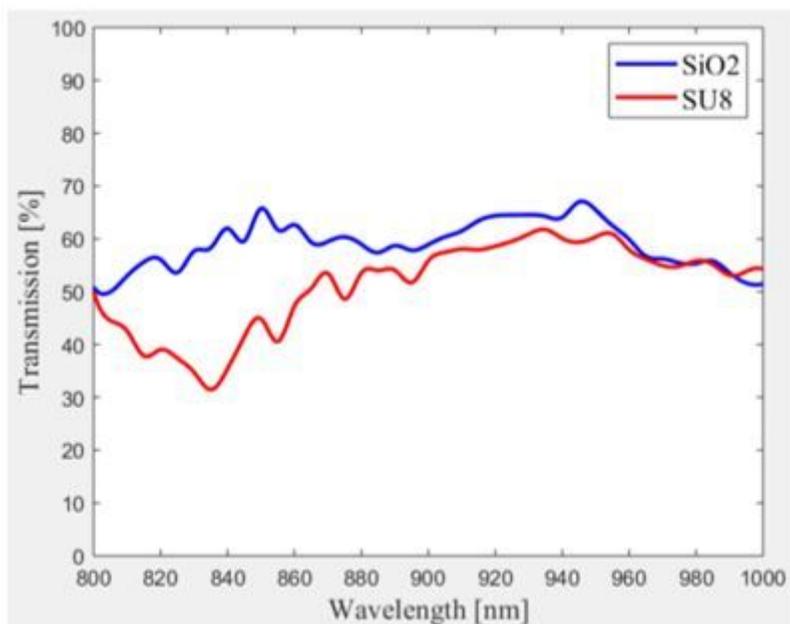


Figure 6

Transmission results (percentage) for SVPCs designed with SiO₂ and SU-8 in the near-IR region from 800-1000 nm using FDTD simulations in Lumerical.

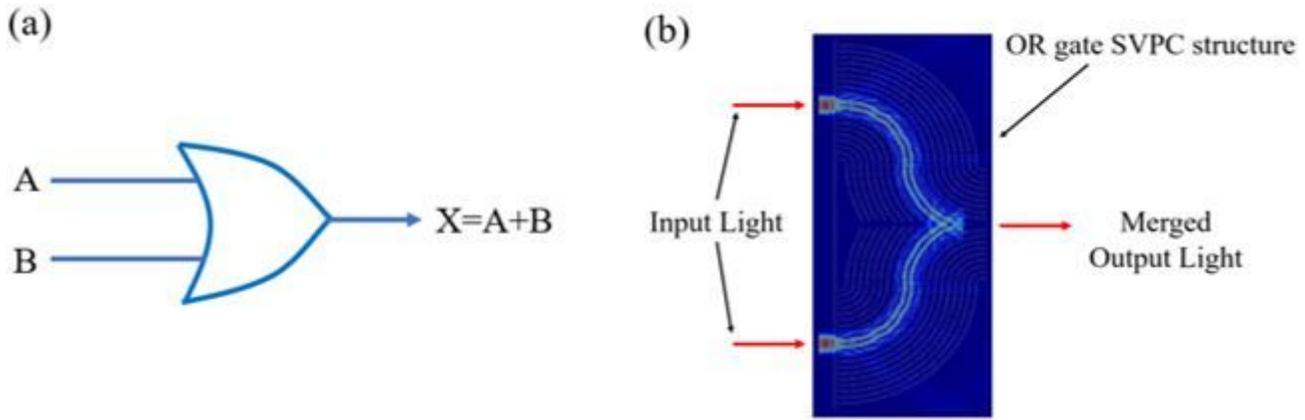


Figure 7

(a) Electronic OR gate; (b) 2D SVPC model for optical OR gates.

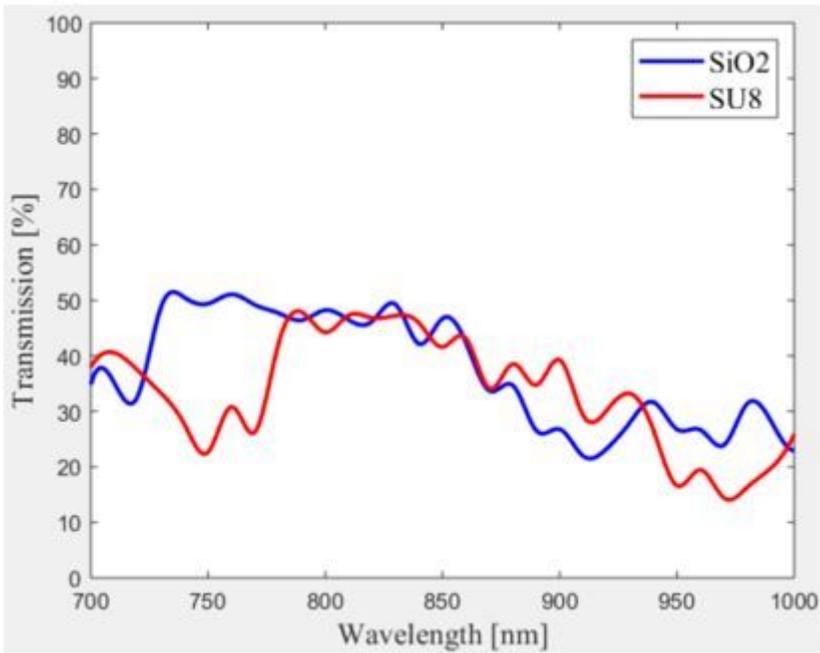


Figure 8

Transmission results for optical logic gate (OR gates) with two different low-refractive index materials. Results for SiO₂ and SU-8 are shown by the blue and red lines, respectively.

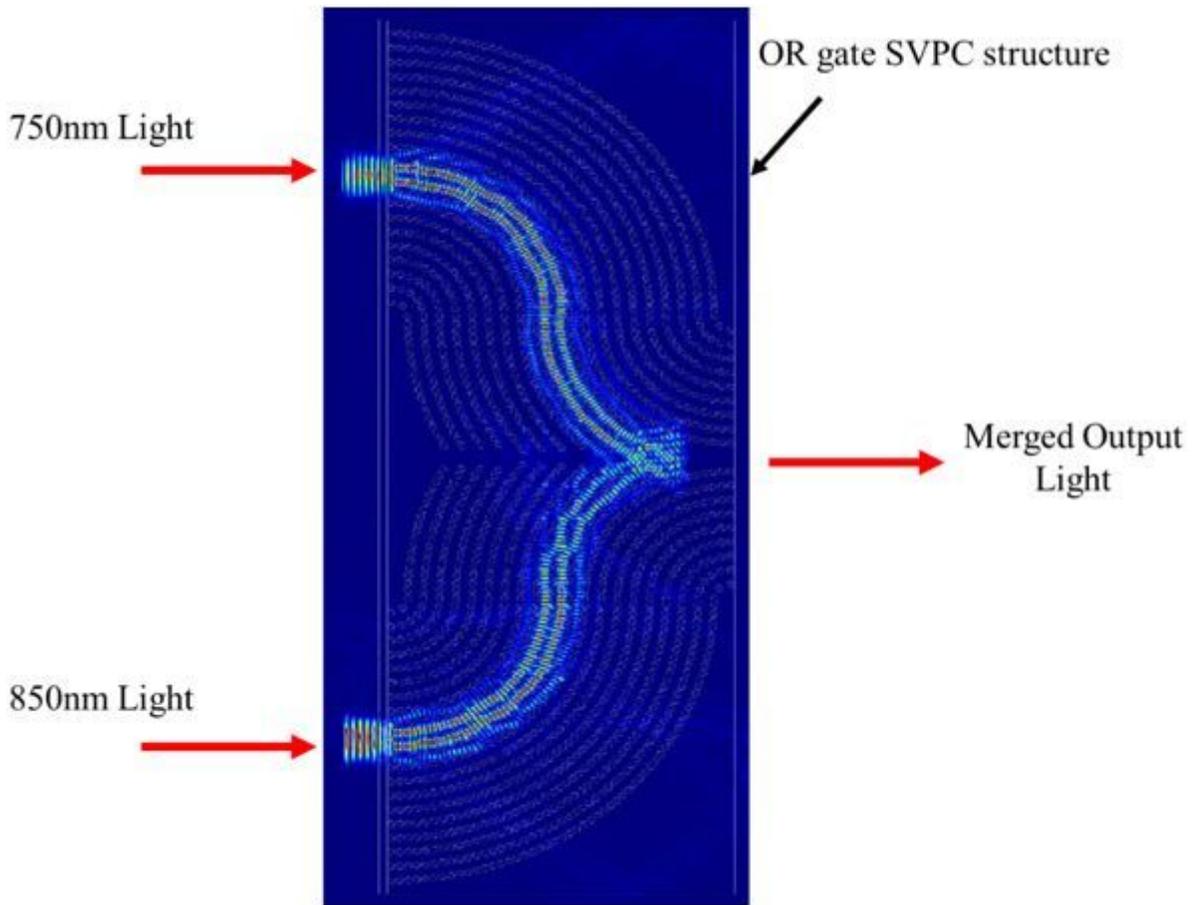


Figure 9

SiO₂ SVPC optical logic gate for two dissimilar wavelengths