Feasibility Assessment and Analysis of a Forward Injected Photonic Crystal Device

Mark T. Tinker, Member, IEEE, Yonghao Cui, and Jeong-Bong Lee, Senior Member, IEEE

Abstract—A forward injected photonic crystal device design has been proposed for the purpose of injecting a high carrier concentration across the intrinsic region of a p-i-n diode formed across the waveguide of a photonic crystal in order to modulate the refractive index of the waveguide and generate a highly compact optical device. A numerical model was developed and evaluated both to assess the feasibility of this particular approach and to optimize the design. Carrier concentrations as high as 5.5x10^17 cm^-3 were injected across the intrinsic region of a p-i-n diode formed across the waveguide of an InP photonic crystal slab by highly forward biasing the device. This level of injection was capable of causing a negative shift in the refractive index of approximately -0.004 with response times of around one nanosecond. The refractive indices and absorption coefficients generated during this analysis were then applied to a photonic crystal waveguide in order to assess the feasibility of developing a compact optical device using a strongly forward injected p-i-n diode.

Index Terms—Electrooptic devices, optical modulation, optical planar waveguides, optical propagation in plasma media, p-i-n diodes.

I. INTRODUCTION

T

wo-dimensional photonic crystals offer the potential to generate exceedingly small microcircuits capable of handling and manipulating light at dimensions on the order of microns. Although considerable progress has been made towards developing and miniaturizing the passive components of these systems [1]-[5] considerably less progress has been made towards miniaturizing the active components used in these systems [6]-[15]. This effort has been hampered in part by the fact that most active optical devices range from several hundred microns to a few millimeters in size as a result of the weak optical effects typically generated inside these devices [16]-[18].

Much smaller devices can be achieved by inducing a much larger change in the refractive index inside the device. However, this is not straightforward. A variety of authors have proposed the use of liquid crystals in two-dimensional photonic crystals to shrink the size of the device [6]-[8]. By selectively filling the open regions in a photonic crystal structure with liquid crystals and then applying a voltage to the device, large changes in the refractive index of around 0.2 can be achieved. This size of change can be used to shrink the size of these devices down to the order of microns or tens of microns in size. However, it is extremely difficult to actually develop this type of device in practice since a fluid medium must somehow be successfully integrated with an exceedingly small two-dimensional photonic crystal device. In addition, the response time of these types of devices would ultimately be limited to only a few milliseconds.

The thermo-optic effect can also be used to shrink the size of the device [9]-[12]. Higher temperatures of a hundred to several hundred degrees centigrade can induce changes in the refractive index ranging from around 0.02 to 0.10. Response times on the order of microseconds can potentially be achieved by this approach. These devices can be heated by either thin-film metal microheaters that have been deposited on top of an oxide deposited over the photonic crystal device or by the resistive heating of highly doped silicon heating elements positioned directly adjacent to the photonic crystal. A tunable photonic crystal filter and two separate Mach-Zehnder photonic crystal modulators have already been demonstrated. One of these interferometers was able to achieve a length as small as 12 μm by heating one of the arms of the interferometer to a temperature of 250 °C. Even higher temperatures can probably be achieved. However, the microsecond response times exhibited by these systems will ultimately limit the applicability of this technique to somewhat slower applications.

The response time of the device can be reduced even further by using either an optical control pulse or an electrical device [13]-[15]. One approach uses light to induce saturation absorption in InAs quantum dots deposited on top of a GaAs photonic crystal waveguide to change the refractive index. This approach uses a fairly complex arrangement of optical couplers with a Mach-Zehnder interferometer to modulate the light. This technique generates a change in the refractive index of -0.001 by transmitting an optical control pulse through one arm of the interferometer. The total length of the device is 600 μm long with a 300 μm active length. The total
response time of the device is approximately 100 ps. The response time is ultimately limited by the carrier relaxation time in the device. The active length of the device is reduced appreciably by designing the waveguide so that it propagates light in a frequency regime in which the light propagates with a slow group velocity \( v_g \). This smaller group velocity induces a much larger change in the phase of the light causing the device to shrink by approximately \( c/v_g \). However, this approach also reduces the bandwidth of the device proportional to the group velocity \( v_g \) severely restricting the available bandwidth of operation.

An alternative approach uses a p-i-p diode to inject holes across one arm of a silicon Mach-Zehnder photonic crystal modulator to cause the necessary phase shift [15]. This approach induces only a small shift in the refractive index that is again enhanced by using a slow group velocity. A Mach-Zehnder interferometer with an active length of 80 \( \mu \)m was ultimately achieved. However, the device must be operated within a very narrow frequency band very close to the cut-off frequency in order to achieve this size of device.

Although the size of the device might be reduced by using a slow group velocity, this would also severely restrict the bandwidth of operation and also make the system extremely susceptible to small changes in temperature and to small changes in dimension. This could render the device impractical for real applications since the device could require both exceedingly tight processing tolerances and extremely tight temperature control in order to generate a stable and functional device. The best approach for shrinking the size of the device would be to develop a device which could induce relatively large changes in the refractive index while still exhibiting fast response times.

Forward injection of an electron-hole plasma across a photonic crystal waveguide offers the potential of inducing changes in the refractive index that are appreciably greater than 0.001 while still achieving response times on the order of nanoseconds [19], [20]. Smaller devices could then be achieved without having to restrict the bandwidth of the device. Even smaller devices could then be achieved by using a slow group velocity provided the resultant bandwidth of operation and design tolerance can be tolerated. The proposed device concept is discussed in greater detail below.

II. DEVICE DESIGN AND ANALYSIS

A. Device Concept

A top-view of the proposed forward injected device is shown in Fig. 1. A highly doped p-i-n diode is first formed across a photonic crystal waveguide as shown above. A forward voltage is then applied to the device in order to inject a plasma of electrons and holes across the intrinsic region of the waveguide. This change in the carrier density reduces the refractive index of the waveguide thereby generating an active device that can be used to control a wide variety of different optical devices. The plasma generates a relatively large negative shift in the refractive index by both the plasma effect and bandfilling that is inversely proportional to the effective mass. Therefore this effect is most pronounced in semiconductor compounds such as GaAs and InGaAsP because of their relatively small electron effective masses [20]. However, the refractive index is also increased by the thermo-optic effect [21] as the temperature is increased by the heat generated from both the resistive heating and the increased recombination kinetics occurring at higher current densities. This effect begins to predominate at sufficiently high current densities ultimately limiting the current density that can be used to generate a functional device. Consequently, the design of the any device must consider both the effect of the decrease in the refractive index caused by the injected plasma versus the increase in the refractive index caused by increasing the temperature.

1) P-I-N Diode Theory: Strongly forward injecting this device generates an electron-hole plasma within the intrinsic region effectively decreasing the refractive index in this region and modulating the optical properties of the device. A simplified one-dimensional schematic of the device is shown in Fig. 2(a) where the p-side of the device has length \( d_p \), the intrinsic region i has width 2d, the n region of the device has length \( d_n \), and the metal contacts metal are shown to the left and right of the device. The common logarithm of the carrier concentration generated across a forward injected device versus position is shown in Fig. 2(b) where p is the hole carrier concentration, n is the electron carrier concentration, \( n_{A^+} \) is the ionized acceptor concentration, and \( n_{D^+} \) is the ionized donor concentration [22].

![Diagram](image_url)
The middle region of the device must necessarily be quasi-neutral during forward injection as shown in Fig. 2(b) since a large excess charge cannot accumulate in this region during injection because of the high concentration of carriers in this area. The current density resulting from the recombination of the electrons and the holes in the middle region of the device $i_m$ is given by the simple equation

$$ i_m = n_{ave} \frac{2de}{\tau_i} $$

where $n_{ave}$ is the average carrier density in this area, $\tau_i$ is the carrier lifetime, and $e$ is the electronic charge. Consequently, the current generated in the middle region of the device increases as the average carrier concentration $n_{ave}$ increases, the width of the intrinsic region $2d$ increases, and the carrier lifetime $\tau_i$ decreases [22].

An electron minority carrier distribution is also generated during forward injection on the p-side of the device and a hole minority carrier distribution on the n-side of the device as shown in Fig. 2(b). The width of the electron carrier distribution would generally be much larger than the hole carrier distribution since the electron mobility of most semiconductors is typically much larger than the hole mobility. These diffusion currents can be decreased by increasing the doping concentration in order to suppress the minority carrier concentration.

2) Recombination Kinetics: The carrier lifetimes controlling the current densities generated in the various regions of the device shown in Fig. 2(b) are directly related to the carrier recombination kinetics in these areas. The general equation for the carrier recombination rate is given by

$$ R = \frac{np - n_i p_i}{(n + n_i) \tau_h} + \left( \frac{p + p_i}{\tau_e} \right) + S_v \frac{np - n_i p_i}{n / v_h + p / v_e} + B(np - n_i p_i) + C \frac{n^2 + p^2}{2} (np - n_i p_i) $$

where $R$ is the recombination rate, $n$ is the electron carrier density, $p$ is the hole carrier density, $n_i$ and $p_i$ are the electron and hole carrier densities at thermal equilibrium, $\tau_h$ is the hole carrier lifetime in the bulk, $\tau_e$ is the electron carrier lifetime in the bulk, $S_v$ is the surface area per unit volume, $v_h$ is the surface recombination velocity of holes, $v_e$ is the surface recombination velocity of electrons, $B$ is the radiative recombination coefficient, and $C$ is the Auger coefficient [19], [23], [24]. Generally, the defect trap density and the equilibrium carrier concentration are small compared to the electron and hole carrier concentrations generated during forward injection and in highly doped materials and can be safely ignored during any calculations.

Since the surface area $S_v$ is very large in a photonic crystal, the surface recombination rate will be much larger than the bulk defect recombination rate within a photonic crystal device. In addition, radiative recombination and Auger recombination will only begin to dominate the recombination kinetics at very high carrier densities. Therefore, the surface recombination rate will typically control the recombination kinetics occurring in a photonic crystal device [19], [23]-[31].

Generally, materials with a high surface recombination rate are not appropriate for developing a forward injected photonic crystal device since they cannot sustain a high carrier density. Since GaAs exhibits an extremely high surface recombination velocity of approximately $10^6$ cm/s, it is not capable of sustaining a large change in the carrier concentration during forward injection. However, the InGaAsP quaternary alloys, which demonstrate surface recombination velocities of approximately $10^4$ cm/s, can sustain much higher carrier levels during forward injection and are a much more suitable material for a forward injected device [19], [23]-[31].

3) Thermal Transport: The energy generated by resistive heating and carrier recombination during forward injection also causes the temperature to rise in the device causing a positive shift in the refractive index. Assuming that the photonic crystal device has been released from the underlying substrate, the heat must be primarily transported away from the center of the device through the semiconductor to the metal contacts and ultimately down through the underlying substrate lying underneath the metal interconnects. Since the thermal conductance through the electrical interconnects will usually be very high compared to the thermal conductance through the semiconductor, the temperature at the contacts should normally be maintained fairly close to room temperature thereby facilitating the flow of energy away from the device.

One of the key objectives of this design is to minimize the temperature rise in the device. Therefore, the electrical resistance of the highly doped regions shown in Fig. 2(a) should be decreased as much as possible by increasing the doping levels in both the P" and the N" regions of the device. This should also decrease the overall current density generated in the device by suppressing the diffusion tails on both sides of the device. In addition, the distance to the electrical contacts from the waveguide shown in Fig. 2(a) should also be decreased as much as possible in order to reduce the amount of resistive heating generated in the device and facilitate the transport of heat away from the waveguide.

The thermal conductivity of the device should also be increased as much as possible by choosing an appropriate material. Although the quaternary InGaAsP compounds exhibit a significantly lower electron effective mass than InP [20], the thermal conductivity of these compounds is very low, averaging only around 5 W/m°C. InP however demonstrates a much higher thermal conductivity of 68 W/m°C. Therefore, devices made from InP are much more amenable for designing a forward injected device [28].

B. Device Design

1) Device Layout: The final design generated for an InP-based forward injected device is shown in Fig. 3(a) and the doping profile shown in Fig. 3(b). The doping profile is sectioned midway between the top and middle row of air holes in the device. The left side of the waveguide is heavily p-doped and the right side of the waveguide is heavily n-doped using ion implantation prior to the formation of the photonic
The thickness of the InP slab used to generate the device was assumed to be 0.25 μm thick.

The device was designed using a lattice spacing equal to 0.45 μm and a hole diameter near 0.25 μm in order to transmit transverse-electric (TE) light through the waveguide at the telecommunication wavelength of 1550 nm. Two triangular photonic crystal arrays each five rows wide are etched through the InP slab on each side of the linear photonic crystal waveguide. The location of the metal contacts are positioned around 1.0 μm beyond the end of the air holes on both sides of the device near the expected center of any real contacts that would need to be deposited on top of the InP surface in an actual device. The number of rows of air holes used in this device is reduced as much as possible in order to reduce the distance to the electrical contacts and to the underlying substrate. This both reduces the electrical resistance of the device while at the same time reducing the distance to the contacts and to the underlying substrate in order to facilitate heat transport.

Two triangular photonic crystal arrays each five rows wide are etched through the InP slab on each side of the linear photonic crystal waveguide. The location of the metal contacts are positioned around 1.0 μm beyond the end of the air holes on both sides of the device near the expected center of any real contacts that would need to be deposited on top of the InP surface in an actual device. The number of rows of air holes used in this device is reduced as much as possible in order to reduce the distance to the electrical contacts and to the underlying substrate. This both reduces the electrical resistance of the device while at the same time reducing the distance to the contacts and to the underlying substrate in order to facilitate heat transport.

![Diagram](image.png)

Fig. 3. (a) Two-dimensional image of doping distribution generated across an InP photonic crystal device and (b) doping profile generated across the device.

2) Doping Profile: The doping concentration of both the p-region and the n-region should be increased as much as possible in order to suppress the parasitic diffusion currents resulting from the injection of minority carriers into the heavily doped regions of the device and to lower the electrical resistance [28], [32]-[34]. Consequently, the doping concentration was raised to a value of $3.0 \times 10^{18}$ cm$^{-3}$ on the P$^+$ side of the device and to a value of $5.0 \times 10^{17}$ cm$^{-3}$ on the N$^+$ side of the device as shown in Fig. 3(a) and (b).

The doping level in the middle region of the device was raised to a donor concentration level of $5.0 \times 10^{17}$ cm$^{-3}$ in order to minimize the positive shift in the refractive index that would be induced by an electron-hole plasma by band gap narrowing at lower carrier levels. Since this effect is largely controlled by n-type carriers at these concentration levels, this drop is largely eliminated by already incorporating a moderate level of n-type dopant in this area. Incorporation of this dopant should also help suppress the ingress of p-type carriers into the middle region of the device capable of causing high absorption [20], [35]-[37].

The lateral straggle for the doping profiles generated using both p and n-type dopants was assumed to be 0.13 μm from data acquired from various ion implantation studies reported on InP in the literature [28], [32]-[34]. Generally, it is fairly easy to generate good doping profiles using n-type dopants in InP. Generating good doping profiles using p-type dopants in InP is generally more problematic but good doping profiles can still be achieved by using either co-implants or by careful control of the rapid thermal annealing cycle.

Placing these profiles closer to the center of the waveguide increases the injected carrier concentration in the middle region of the device by decreasing the diffusion distance across this region as shown in Fig. 2(b). However, this ultimately reduces the overall increase in the carrier concentration across the waveguide as the width of this region becomes less than the width of the waveguide. Placing these profiles further away from the center of the device ultimately decreases the carrier density by increasing the diffusion distance across the device. A series of device simulations were run to determine the optimal position of the doping profiles in order to maximize the value of the average carrier concentration across the waveguide. Ultimately, these profiles were placed 0.55 μm from the center of the device.

C. Numerical Simulations

1) Methodology: Numerical simulations were performed using the Sentaurus Device modeling software. A fully coupled Newton method was first used to self-consistently solve the Poisson and electron and hole continuity equations without coupling to the temperature. The solution for the temperature was then coupled to the solutions to the Poisson and electron and hole continuity equations using a Gummel approach. Fermi-Dirac statistics were employed in all simulations.

The boundary conditions for this problem were applied to the far left and right hand sides of the structure. A voltage ranging from 0 V up to 1.8 V was applied to the anode on the left hand side of this system while the cathode situated on the right hand side of the structure was held at ground in order to generate a forward injected device. The temperatures at the left and right hand sides of the device were held at room temperature since both contacts were assumed to be attached directly to large metal heat sinks which should strongly suppress the temperature of the device right at the contacts.
2) Material Properties: A large number of different material parameters had to be assigned in order to successfully model this device. The most important parameters are discussed below.

The doping dependence of the low-field mobility for electrons and holes in InP was modeled using the Arora model [38]. The mobility of the electrons drops from around 5000 cm$^2$/V-s at low doping concentrations to around 1200 cm$^2$/V-s at 5.0x10$^{18}$ cm$^{-3}$ and the mobility of the holes drops from around 170 cm$^2$/V-s at low doping concentrations to around 50 cm$^2$/V-s at 3.0x10$^{18}$ cm$^{-3}$ [39]. Note that the mobility of the electrons is approximately twenty-five times higher than that for holes in InP. Consequently, the electrons on the P$^+$ side of the device should generate a much longer diffusion tail than the holes on the N$^-$ side of the device. Additionally, the holes on the P$^+$ side of the device will exhibit a much higher electrical resistivity than the electrons on the N$^-$ side of the device.

The various parameters shown in Eq. (2) also needed to be determined for each region of the device shown in Fig. 3(a) in order to accurately model the recombination kinetics of the device. The bulk recombination rate in p-type material is generally much faster than that of either n-type material or intrinsic material in InP. Consequently, the electron carrier lifetime $\tau_e$ in InP must be much shorter than the hole carrier lifetime $\tau_h$. Available carrier lifetime data indicates that the hole carrier lifetime $\tau_h$ is approximately 20 ns in InP and the electron carrier lifetime $\tau_e$ approximately 1 ns [28], [40], [41].

Similarly, the surface recombination velocity $v_s$ is also generally considered much faster in p-type material than in n-type material or intrinsic material [23]-[31]. Consequently, the surface recombination velocity of electrons $v_e$ must be much faster in InP than the surface recombination velocity of holes $v_h$. Typically, $v_e \leq $ 1x10$^4$ cm/s in both n-type material and intrinsic material and around ten times faster than this in p-type material. Consequently, $v_h$ was assigned a value of 5.0x10$^7$ cm/s and $v_e$ was assigned a value of 5.0x10$^4$ cm/s in order to determine the different surface recombination rates occurring in each region of the device. The overall surface recombination rate was then determined in each region of the device by first calculating the surface area per unit volume $S_e$ in each region shown in Fig. 3(a) by using a slab thickness of 0.25 $\mu$m and then determining the overall surface recombination rate of each region by using Eq. (2).

Finally, the radiative recombination coefficient $B$ was assumed to be 2.5x10$^{-10}$ cm$^3$/s and the Auger recombination coefficient $C$ was assumed to be 1.0x10$^{-30}$ cm$^6$/s in accordance with a variety of data available in the literature [23], [41], [42].

The value of the thermal conductivity of doped InP decreases with doping concentration [28]. The thermal conductivity was assigned a value of approximately 51 W/m$^2$C in the highly doped P$^+$ and N$^-$ regions of the device and a value of 57 W/m$^2$C in the middle region of the device.

3) Steady-State Analysis: The device was then forward biased to 1.80 V generating an average current density of 1.0x10$^5$ Amps/cm$^2$. This current density increases to a maximum of 2.8x10$^5$ Amps/cm$^2$ in between the air holes. The electron diffusion current dominates the transport kinetics across the entire device because of the extremely high mobility of the electrons. These current densities are typical of the maximum current densities that can generally be sustained in an InP-based device [43].

The electron density generated in this device is shown in Fig. 4(a) and (b). The electron density drops from around 5.0x10$^{18}$ cm$^{-3}$ on the n-side of the device to an average density of 1.1x10$^{18}$ cm$^{-3}$ in the middle region of the device before exhibiting a long diffusion tail on the p-side of the device. Consequently, the injected electron carrier density in the middle region of the device is increased by almost 6.0x10$^{17}$ cm$^{-3}$. The hole density is also shown in Fig. 5(a) and (b). The hole density rises to around 3.6x10$^{16}$ cm$^{-3}$ on the p-side of the device due to high level injection before dropping to an average density of 5.5x10$^{15}$ cm$^{-3}$ in the middle region of the device. The hole density then drops abruptly on the n-side of the device because of the short diffusion tail of the holes in the n-region and the high electron potential caused by the highly degenerate nature of the electrons on the n-side of the device.

The temperature gradient generated in the device at steady-state is shown in Fig. 6(a) and (b). The temperature rises around 23 °C on the p-side of the device because of the effect of high resistive heating on that side of the device and around 19 °C across the waveguide. This temperature rise is a significant issue which could largely negate the effectiveness of this device. To mitigate this effect, the device should be operated by switching between the ON and OFF states using a 20% duty cycle in order to both reduce the value of the temperature rise and control the variability of the temperature fluctuations. This would cause an average increase of only around 1.9 °C across the waveguide at a current density of 1.0x10$^5$ Amps/cm$^2$. 

![Electron Density](image1)

![Electron Density](image2)

Fig. 4. (a) Two-dimensional image of electron density generated by forward injecting the photonic crystal device to 1.80 V and (b) graph of electron density versus position.
The change in the refractive index was calculated using the relation [20], [44]

\[ \Delta n = -8.0 \times 10^{-21} \cdot \Delta N + 2.0 \times 10^{-4} \cdot \Delta T \]  

where \( \Delta n \) is the change in the refractive index, \(-8.0 \times 10^{-21}\) is the change in the refractive index caused by the injected plasma given in \( \text{cm}^3 \), \( \Delta N \) is the average change in the carrier density in the middle region of the device given in \( \text{cm}^{-3} \), \( 2.0 \times 10^{-4} \) is the thermo-optic coefficient given in \( \degree \text{C}^{-1} \), and \( \Delta T \) is the average change in the temperature in the middle region of the device given in \( \degree \text{C} \). The change in the carrier density is effectively equal to the average hole density injected into the middle region of the device since the initial hole density in this region is essentially zero. The change in the refractive index versus current density rises to an absolute value of approximately 0.0041 at a current density of 1.0 \times 10^5 \text{ Amps/cm}^2 as shown in Fig. 7.

4) Transient Analysis: A transient analysis was performed to assess the response time of the device. Rise times were calculated by evaluating the time required to increase the average carrier concentration from 10 to 90% of its maximum value and fall times were calculated by evaluating the time required for the average carrier density to fall from 90 to 10% of this maximum value. The response time of this device is shown in Fig. 8. The rise time of the device equals 1.35 ns and the fall time 0.50 ns. This is roughly similar to the recombination kinetics of the device which is on the order of 1 ns.
### III. OPTICAL DESIGN AND ANALYSIS

#### A. P-I-N Diode Optical Coefficients

The high doping levels used on the p-side and n-side regions of the p-i-n diode and the carrier density of the forward injected plasma cause large changes in both the refractive indices and absorption coefficients in these areas. The refractive indices $n$ and absorption coefficients $\beta$ of these different areas are shown in Table 1 both with and without a forward injected plasma injected across the middle region of the diode [19], [20], [35]-[37]. The optical coefficients were calculated for the p-i-n diode shown in Fig. 3(a) and (b). The effect of the plasma was calculated using an injected carrier density of $5.5 \times 10^{17}$ cm$^{-3}$. These parameters were used to design and evaluate a potential photonic crystal device.

Absorption is a particularly serious problem in these systems and must be considered very carefully. P-side absorption is particularly severe. However, since the intensity of the light does not extend very far into the photonic crystal situated on either side of the device, the effect of either p-side or n-side doping is fairly limited. The effect of the injected plasma on the transmitted light, however, is much more substantial since the field of the transmitted light is tightly constrained to the region of the waveguide. The absorption of light in the plasma would cause approximately a 5 dB loss over approximately 1000 μm. However, this distance can probably be extended up to several millimeters or even larger when no plasma is injected into the channel since absorption would occur only through the doping on the p-side and n-side regions of the device and through the moderately light n-type doping in the channel.

#### B. Optical Analysis

A typical photonic crystal waveguide was designed by using the two-dimensional finite-difference time-domain method 2D FDTD using a lattice spacing of 0.45 μm with a hole diameter of 0.248 μm equal to 0.55 times the lattice spacing in both the $p^+$ and $n^+$ regions of the p-i-n diode as shown in Fig. 9. The $p^+$, $n^+$, and middle regions of the diode have been assigned the values of the refractive indices and absorption coefficients shown in Table 1 in order to simulate the device.

The refractive index profiles formed across the device generated with and without forward injection are shown in Fig. 10. These refractive index profiles will alter the optical characteristics of the device and are simply the result of the necessary doping required to actually operate the device. These profiles have not been designed to form an index-guided waveguide as commonly occurs in many waveguides. The light is actually guided down the waveguide by the action of the photonic crystal lattice situated on both sides of the waveguide.

These refractive indices were adjusted using the effective index method using a thickness of 0.25 μm by computing analytical solutions of the transcendental waveguide equation in order to simplify a three-dimensional 3D computational problem to a two-dimensional one. The effective indices $n_{\text{eff}}$ generated for various regions of the device are also shown in Table 1. This technique uses a 2D FDTD simulation using the effective indices calculated by this technique to approximate an extremely computationally intensive three-dimensional simulation and has proven effective at generating good approximations to a three-dimensional simulation problem while drastically reducing the computational time required for analysis [12], [45], [46].

![Fig. 9. Photonic crystal p-i-n diode structure showing Gaussian TE light source on left and detector on right (green cross) designed with a lattice constant of 0.45 μm and a hole diameter of 0.248 μm.](image)

The absorption coefficients used during these simulations in each region of the device were calculated using the relation

$$\beta_T = \Gamma_S \beta + (1 - \Gamma_S) \beta_A$$

(4)

where $\Gamma_S$ is the transverse confinement factor in the slab, $\beta$ is the absorption coefficient given in Table 1, $\beta_A$ is the absorption coefficient in the air which is equal to zero, and $\beta_T$ is the total overall absorption coefficient for light being transmitted through the slab. For the fundamental transverse mode, $\Gamma_S$ can be approximated using the relation

$$\Gamma_S = D^2/(2 + D^2)$$

(5)

where $D$ is the normalized waveguide thickness given by

$$D = \frac{2\pi}{\lambda} \sqrt{\Delta^2}$$

(6)
where \( \lambda \) is the wavelength, \( n \) is the refractive index, \( n_a \) is the refractive index of the air which is equal to one, and \( d \) is the thickness of the slab. The absorption coefficients generated for light confined in the vertical direction of the slab are also shown in Table 1 [23], [24].

The device was then simulated by applying these effective indices and absorption coefficients to the different regions of the device. Transverse-electric TE light was then input from the left side of the device using a wavelength of 1550 nm as shown in Fig. 9.

The magnetic field amplitude generated without a plasma is shown in Fig. 11(a). The magnetic field amplitude has been tightly constrained to the waveguide and shows no noticeable loss in intensity along the length of the device. The magnetic field amplitude generated using an injected plasma is also shown in Fig. 11(b) for direct comparison. The magnetic field amplitude generated with the plasma has also been tightly constrained to the waveguide and again shows no noticeable loss in intensity along the length of the waveguide as would be expected given the small level of additional absorption loss that would be expected in the plasma over this distance. Both images clearly demonstrate the basic functionality of the device.

These devices were also evaluated using a length of 50 \( \mu \)m in order to better ascertain the expected intensity loss occurring down the waveguide. Light transmitted down the waveguide without a plasma exhibited a loss of approximately 0.25 dB over the 50 \( \mu \)m length of the waveguide. Loss appeared to occur from a small amount of leakage through the five rows of the photonic crystal situated on each side of the device. Light transmitted down the waveguide with a plasma exhibited a loss of approximately 0.50 dB over the 50 \( \mu \)m length of the device. This additional level of loss would be expected given the anticipated level of loss due to absorption. Consequently, a 100 \( \mu \)m long device would be expected to demonstrate a loss of 0.50 dB without injection and a 1.0 dB loss with injection.

The small amount of leakage occurring through the photonic crystal device can be largely eliminated by increasing the width of the photonic crystal situated on each side of the device to seven rows. Consequently, the loss of a 100 \( \mu \)m long device could be reduced to around a 0 dB loss without injection and a 0.5 dB loss with injection by using a wider device. However, this would also cause a significant increase in the temperature of the device reducing the effectiveness of the design.

C. Optical Design

The active length of a Mach-Zehnder interferometer was evaluated by using the phase shift that could be induced by a forward injected device. Since the phase shift induced by the change in the refractive index is inversely proportional to the group velocity, the size of the active length of a Mach-Zehnder interferometer necessary to induce a 180° phase shift can be reduced substantially by decreasing the group velocity of the transmitted light. This can be achieved by designing the interferometer close to the cutoff frequency. However, this also decreases the bandwidth of the device. Consequently, the active length of the device was estimated at a frequency much higher than the cutoff frequency of the waveguide and also much closer to the cutoff frequency in order to determine the potential range of sizes that can be generated by using a forward injected device [47], [48].

Fig. 11. (a) Magnetic field amplitude through waveguide with no injection and (b) magnetic field amplitude with injection at 1550 nm for a device designed using a lattice constant of 0.45 \( \mu \)m and a hole diameter of 0.248 \( \mu \)m.
The group velocity \( v_g \) can be derived from the resultant band diagram for the TE-like guided modes shown in Fig. 12. This diagram shows the guided modes propagated by the photonic crystal waveguide within the photonic band gap, or PBG, of the device. Light situated beneath the light line is constrained by total internal reflection within the waveguide. The relevant mode for this analysis is the bottom of the two modes which extends from a normalized frequency of 0.277 at a wavelength of 1620 nm up to the light line near a normalized frequency of 0.300 at a wavelength of 1500 nm. Light extending beyond the light line will no longer be constrained by total internal reflection to the waveguide. The cutoff range in which light can no longer propagate down the waveguide extends from a normalized frequency of 0.271 at a wavelength of 1660 nm to the cutoff frequency of 0.277 [47], [48].

The group velocity \( v_g \) can be derived by taking the slope of the guided mode in the band diagram. Consequently, the group velocity approaches zero near the cutoff frequency and increases as the slope increases as it gets closer to the light line. The group velocity versus normalized frequency is shown in Fig. 13 where the group velocity extends from zero near the cutoff frequency of 0.277 to 0.31 at a normalized frequency of 0.300. The group index \( n_g \) given by the equation

\[
 n_g = \frac{c}{v_g}
\]

is also shown on the right hand axis and is shown to increase gradually from a normalized frequency of 0.300 to a normalized frequency of 0.285 above which the group index begins to rise very rapidly [47], [48].

Finally, the phase shift versus frequency can be calculated from the corresponding group velocity using the change in the refractive index of 0.0041 occurring during forward injection as shown in Fig. 14. The phase shift is shown as the number of degrees per lattice spacing \( a \) where \( a \) is equal to 0.45 \( \mu \)m. Consequently, the active length of an interferometer arm would be expected to be approximately 160 \( \mu \)m at a normalized frequency of 0.290 corresponding to a wavelength of 1550 nm but would be expected to drop dramatically to around 50 \( \mu \)m at a normalized frequency of 0.281 corresponding to a wavelength of 1600 nm. In principle, the normalized frequency can be decreased to any arbitrary value at a given wavelength by simply reducing the lattice spacing of the photonic crystal in order to increase the phase shift and decrease the length of the device [47], [48].

However, the transmission loss also increases rapidly as the device approaches the cutoff frequency limiting the ultimate size of the device. This loss is due to three primary sources. The principal source of the loss is caused by the loss of light that is reflected out of the waveguide as the wavelength approaches within 20 to 30 nm of the cutoff frequency, or approximately 1600 nm in this particular system. The second source of loss occurs as the light spreads out into the photonic crystal and ultimately penetrates the finite size of the photonic crystal device. This can be mitigated by increasing the size of the photonic crystal from five rows to seven rows but will ultimately occur at some point as the device approaches cutoff. The third is actual absorption loss.

The loss remains nearly constant up to 1580 nm as the device begins to approach 100 \( \mu \)m in length. Two-dimensional FDTD analysis indicates that the loss remains...
around 0.50 dB across a device with no injection and 1.0 dB across a device with injection at this length. This loss is comparable to that occurring at 1550 nm and should not preclude the use of this geometry in a practical device. The loss begins to increase near 1600 nm where the device length drops to a length of 50 µm. Loss across a 50 µm device begins to approach approximately 1.0 dB with no injection and 1.5 dB with injection. However, the shorter device length occurring at this frequency should still allow the design of a functional device. Consequently, the extinction loss in the active arm. This causes a total insertion loss of dB in the OFF state. Turning on the current causes an in the active arm thereby generating an extinction ratio of 21 a 0.53 dB loss in the inactive arm compared to a 0.50 dB loss the wavelength relative to the active arm. Since the couple these active devices directly to highly compact forward injected photonic crystal device permits the user to important factor in reducing the waveguide beyond the size of [47]-[52]. Consequently, the ability to tailor the group present device. However, these devices typically exhibit sizes ranging from a few hundred to several hundred microns [49]-[52]. Consequently, the ability to tailor the group velocity to reduce the size of the device appears to be an important factor in reducing the waveguide beyond the size of standard devices. Just as importantly, the ability to develop a forward injected photonic crystal device permits the user to couple these active devices directly to highly compact photonic crystal waveguides which can quickly and abruptly change the direction of light within a highly compact device.

IV. CONCLUSION

The basic feasibility of a forward injected photonic crystal device has been demonstrated via an extremely thorough numerical analysis specifically developed for a forward injected p-i-n diode generated directly across a photonic crystal waveguide formed within a thin InP slab. The p-side and n-side of the device must be heavily doped in order to suppress the parasitic diffusion currents occurring in the highly doped regions of the device and to reduce the effect of resistive heating on the device. A refractive index change of approximately -0.004 was induced by the forward injected plasma with response times on the order of 1 ns. Photonic crystal linear waveguides were modeled using the refractive indices and absorption coefficients associated with a forward injected device. The potential for developing highly compact interferometers using the associated device characteristics was demonstrated.

REFERENCES

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.
Yonghao Cui received his bachelor's degree from Peking University in the microelectronics field in July 2003. After graduation, in August 2003, he joined Strong Microelectronics Company, a circuit design company in Shanghai, China. In the fall semester 2004, he joined the University of Texas at Dallas (UTD), Richardson, to pursue his master's degree. At the same time, he joined the UTD MINDS (Micro-Electro Mechanical System) Laboratory where he performed research in the area of photonic crystals under supervising Professor Dr. Jeong-Bong Lee (JB Lee). He received his master's degree in electrical engineering in August 2006. He is currently continuing his research in the area of photonic crystals within the Ph.D. program at UTD in the MINDS research group under Dr. JB Lee.

Jeong-Bong Lee (S'92-M'97-SM'08) received the B.S. degree in electronics engineering from Hanyang University, Seoul, Korea, in 1986 and the M.S. and Ph.D. degrees in electrical engineering from Georgia Institute of Technology, Atlanta, in 1993 and 1997, respectively. In 1999, he joined Louisiana State University (LSU), Baton Rouge, as an Assistant Professor. Then, in May 2001, he moved to the University of Texas at Dallas (UTD), Richardson, where he is currently a tenured Associate Professor in the Department of Electrical Engineering. His current research interests include microelectromechanical systems (MEMS)/nanoelectromechanical systems (NEMS) for biomedical, RF, and photonics applications. He is a recipient of the National Science Foundation (NSF) Career Award in 2001. Since 2007, he has served as a member of the external review panel for the Microsystems division at Sandia National Laboratories.