Design proposal for a low loss in-plane active photonic crystal waveguide with vertical electrical carrier injection

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Abstract: We propose an active waveguide design that provides both low propagation losses (≤ 20 dB/cm) and the capability for electrical pumping of the photonic crystal waveguide with a vertical contacting scheme. A careful estimation of a large number of parameters is required in order to obtain both properties. The proposed device supports single mode operation at the telecom wavelength $\lambda = 1550$ nm and is suitable for the implementation of in-plane active photonic crystal devices, such as semiconductor optical amplifiers and lasers.

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OCIS codes: (130.0250) Optoelectronics; (130.3120) Integrated optics devices; (130.5296) Photonic crystal waveguides; (230.4480) Optical amplifiers; (230.5298) Photonic crystals.

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time the optical losses will increase as we gradually approach a substrate-type design. Contact channel: The wider the channel, the lower is the access resistance; but at the same time the optical losses will increase as we gradually approach a substrate-type design. For the design of a practical device, the proposed structure has to be investigated from both the technology than the ones required for the selective under-etching of the proposed slab-like contact channels. The performance of the device will critically depend on the width $w$ of the contact channel: The wider the channel $w$, the lower is the access resistance; but at the same time the optical losses will increase as we gradually approach a substrate-type design.

For the design of a practical device, the proposed structure has to be investigated from both

\begin{align}
B_n &= \frac{1}{2} \sum_{m=-n}^{n} \frac{1}{2} (n-m)B_{n-m} \\
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\end{align}

1. Introduction

The main interest regarding slab photonic crystal (PhC) waveguides with a weak vertical refractive index contrast is the possibility of electrical pumping active PhC devices. The vertical layer structure allows a straightforward realization of a PIN diode that could be contacted similarly to conventional semiconductor lasers and amplifiers characterized by an efficient vertical current injection [1–4]. However, research on systems with weak contrast of refractive index - also known as substrate-type PhC devices - has been dropped by most research groups due to the currently high propagation losses of single mode PhC waveguides in the order of $600 – 1000 \, \text{dB/cm}$ [5, 6]. On the other hand, membrane-type PhC waveguides exhibit low propagation losses below 10 dB/cm [7–10] but for active membrane-type PhC devices, the current has to be pumped laterally through the PhC [11, 12]. Unfortunately, the ohmic resistance experienced by the laterally injected carriers increases with the filling factor of the PhC [13]. Large filling factors are essential to provide large band gaps in the PhC based devices [14]. To combine the advantages of both approaches, we propose a hybrid structure based on a selective under-etching of the InP cladding layers as shown schematically in Fig. 1. The novelty of the proposed design lies in the combination of the following properties: a) it supports vertical current injection and b) it allows for in-plane operation opposed to the devices proposed in [11,12] which are surface emitters. Our approach bears some similarity to the cavity laser reported by Park et al. [12]: in both cases carriers have to be pumped through a narrow channel. The reliable fabrication of this rod-like channel as used by Park et al. [12] poses much higher demands on the technology than the ones required for the selective under-etching of the proposed slab-like contact channels. The performance of the device will critically depend on the width $w$ of the contact channel: The wider the channel $w$, the lower is the access resistance; but at the same time the optical losses will increase as we gradually approach a substrate-type design.

For the design of a practical device, the proposed structure has to be investigated from both
Fig. 1. The proposed device consists of a PhC waveguide membrane containing a quantum well. The membrane is pumped vertically through two narrow connecting channels. The InGaAs capping-layer is highly doped to allow for a low contact resistance to the metal contact. Furthermore the capping-layer is needed to cover the holes with SiNx for the formation of the contact.

the optical and the electronic perspective. To obtain low optical propagation losses, various structural parameters such as the channel width $w$, the core thickness $t_{\text{core}}$, etc. play an important role, and their effects are all coupled. On the other hand, the channel width $w$ is clearly the dominant structure parameter for the local carrier injection into the QW. Here, the principal unknowns are fabrication-related characteristics: What is the maximum current density $J_{\text{max}}(w)$ that we can pump through a channel of width $w$ without affecting the gain properties of the active material? The answer to this question depends on the amount of surface damage induced during the etching, and on heat conduction and gain properties of the structure. Although we currently cannot determine accurate numbers experimentally from fabricated devices, we try to make a realistic estimate of all those properties and parameters from simple experiments in Sec. 5.

The article is organized as follows: First, we summarize the performance of the proposed device (Sec. 2). This lays the foundation for the ensuing discussions. The physical loss mechanism is reviewed in Sec. 3, and it is shown that low loss waveguide properties can be obtained despite the presence of a contact channel for vertical carrier injection. Finally, we outline the procedure that we carried out to arrive at the final device parameters.

2. Design and performance

The structure presented in Fig. 1 shows a design that is promising for a practical device. The detailed structure parameters, summarizing the following results from the considerations made in Sec. 4 and Sec. 5, are already listed here in Table 1. This PhC waveguide design exhibits low (passive) propagation losses: The propagation loss spectrum (cf. Fig. 2, right panel) shows propagation losses of less than 20 dB/cm for a wavelength bandwidth of $\Delta \lambda = 23.3$ nm and less then 100 dB/cm for a wavelength bandwidth of $\Delta \lambda = 99.6$ nm for a center wavelength $\lambda_0 = 1550$ nm. Despite the low propagation losses, the contact channel width is still as large as $w = 206$ nm, which is sufficient to achieve a typical current density for active devices of $J \approx 0.5 - 5$ kA/cm$^2$.
Table 1. Parameters for the proposed design of Fig. 1. This table summarizes the results from Sec. 4 and Sec. 5. The values given in nm are scaled, such that the best obtained propagation loss value ($\omega a/(2\pi c) = 0.253$) coincides with an operation wavelength of $\lambda = 1550$ nm.

| Parameter                   | Normalized Value $[a]$ | Absolute Value     |
|-----------------------------|------------------------|--------------------|
| Channel width               | $w = 0.526$            | $w = 206$ nm       |
| Channel height              | $h_{top} = 500$ nm     |                    |
| Core layer thickness        | $t_{core} = 0.8$       | $t_{core} = 313$ nm|
| Capping-layer thickness     | $t_{cap} = 150$ nm     |                    |
| Hole radius                 | $r = 0.25$             | $r = 98$ nm        |
| Lattice constant            | $a = 1$                | $a = 392$ nm       |
| Shift of first row of holes | $s_{y1} = 0.02$        | $s_{y1} = 0.02a = 7.8$ nm |
| Shift of second row of holes| $s_{y2} = 0.07$        | $s_{y2} = 0.07a = 27.5$ nm |

3. Theoretical foundations for low propagation losses

The idea behind the proposed design to obtain low propagation loss is to suppress the coupling from the PhC waveguide mode to cladding modes. Theoretically, the cutoff condition of the guided eigenmodes $m$ of a general dielectric waveguide system is commonly written as [15]

$$\varepsilon_m = \max(\varepsilon(\vec{r}_b)), \quad (1)$$

where $\vec{r}_b$ is the boundary located at infinity and $\varepsilon_m$ is the effective permittivity of the eigenmode $m$. According to Eq. (1), guided modes and hence low propagation losses are expected for our device if the PhC waveguide mode is located below the line given by $\omega = ck/n_{InP}$ in the dispersion diagram (green line shown in Fig. 3). However, in a recent publication by Kaspar et al. [16], it was demonstrated, that for structures similar to the one of Fig. 1, the cutoff condition (Eq. (1)) is not relevant to distinguish between lossy and theoretically 'loss-free' modes in a dispersion diagram. Instead, the relevant separatrix is given by the modes of the cladding - referred to as the background (refer to [16] for a detailed definition of the background). In our proposed design, the relevant separatrix is given by the dispersion curve of the fundamental mode of the vertical slab formed by the contact channels of our waveguide. This separatrix is referred to as the background line.

The dispersion diagram in Fig. 3 contains the eigenmodes of the background and of the PhC waveguide. Figure 3 shows the modes propagating in a homogeneous medium with refractive index $n_{air} = 1$ (referred to as the light line - black in Fig. 3) and $n_{InP} = 3.17$ (referred to as the substrate line - green in Fig. 3), the TE (orange) and TM (red) mode of the vertical slab waveguide (the contacting channels) and the modes of the PhC waveguide (blue) within the PhC band gap (gray area). Note that the Fourier representation [17, 18] of the Bloch mode is used in Fig. 3, which has non-zero contributions for all components $k_m = m\pi/a + k_{x0}$. If one spatial Fourier component of the PhC waveguide mode is located above the background line, then light can couple from the PhC waveguide mode to the modes of the vertical slab resulting in a finite propagation loss. A further increase in the propagation losses can be expected when the PhC waveguide mode crosses the light line of the air. Four different regions in the dispersion diagram (points A-D in Fig. 3) can be identified for the shown PhC waveguide mode. For each case, the mode profile is schematically drawn in Fig. 3 and the corresponding locations (A-D) in the dispersion diagram are indicated for the two Brillouin zones. Depending on the location of the PhC waveguide mode in the dispersion diagram, the regions around the waveguide core that contain oscillatory fields change. Simply put, this means that the losses depend on the location in the dispersion diagram.
Fig. 2. Left: band diagram obtained with MPB and a 3D supercell. The size of the dot corresponds to the energy confinement within the core of the PhC waveguide. The straight black line represents the air light line, the dotted red (orange) line represents the dispersion curve obtained from the vertical slab operated in TM (TE) mode.

Right: the red curve is the transmission coefficient for a PhC waveguide of a length of 50 PhC periods. The thick black curve is the corresponding propagation loss $\alpha_{\text{dB}}$. The white (bright blue) background signifies reliable (unreliable) propagation losses according to [6].

In Fig. 2 the significance of the dispersion curves for the propagation losses is confirmed by the numerically computed propagation loss spectrum. The propagation losses are obtained by applying the cutback-method to numerically computed transmission spectra of five different lengths of PhC waveguides $L_i = 10a, 20a, 30a, 40a, 50a$ [6]. The accurate computation of the transmission curves with 3D FDTD requires a realistic excitation through a trench waveguide and a fine mesh resolution of 20 grid points per period $a$. This results in computationally expensive simulations that are carried out on a cluster by using the parallelized version of MEEP [19]. The lowest propagation loss values are obtained for the PhC waveguide mode located below the dispersion curve of the slab TM mode (we find the lowest propagation loss value for $\omega a/(2\pi c) = 0.253$). A significant increase of the propagation losses can be observed for both PhC waveguide modes located above the slab TM mode and above the air light line. Above the air light line, the loss spectrum is dominated by the radiating Fourier component in the first Brillouin zone [18]. In other words, the rather low propagation losses observed above the air light line (around $\omega a/(2\pi c) = 0.285$) correspond to a small relative contribution of the Fourier component in the first Brillouin zone to the complete Fourier series synthesizing to the Bloch mode. It has to be noted that for the simulations of Fig. 2, the waveguide is excited by a $H_z$-field. In the PhC terminology this means that we excite TE-like modes. According
Fig. 3. The influences of the separatrices on the transmission properties. The top figure shows the dispersion curves of the modes of the system in the Fourier representation. The modes are schematically drawn for each of the four points (A-D) that are marked in the dispersion diagram. The PhC waveguide mode is only guided if all Fourier components are below the background line (TE mode of the vertical slab).

To conventional waveguide theory, however, we have a TM mode excitation: The conventions are illustrated in Fig. 4. Due to the symmetry properties of our excitation, the loss-relevant separatrix is the dispersion curve of the TM slab mode.

We conclude, that low propagation losses are obtained, if all spatial Fourier components of the Bloch mode are below the separatrix given by the TM mode of the vertical slab.

Fig. 4. Definitions of the polarization in 2D PhC structures (left) and in slab waveguides (right).
4. Optical design considerations

4.1. Photonic crystal waveguide design

Having explained the principles of the loss mechanism in our design, we can formulate the criteria to obtain low propagation losses. The target is to shift the dispersion relation of the PhC waveguide mode below the dispersion curve (separatrix) of the TM mode of the vertical slab waveguide. This can be achieved by either reducing the contact channel width \( w \) to raise the dispersion curves of the vertical slab TM mode to higher frequencies, or by tailoring (optimizing) the PhC waveguide design, such that the dispersion of the PhC waveguide mode is moved below the background line. For instance, a larger cross-section of the core of the PhC waveguide allows the mode to spread more in the transverse direction, and as a consequence, lowers its frequency.

For a low electrical loss of the current injection, the contact channel width \( w \) should be as wide as possible. Therefore, we start by choosing one of the largest possible channel widths \( w \approx 0.526a \approx 200 \text{ nm} \), for which low optical propagation losses can still be achieved. The choice was made by overlaying the TM dispersion curves for a number of contact channel widths \( w \) with the band gaps of potential PhC waveguides. Then we required that for all frequencies of the photonic band gap, a wave vector \( k_x \) exists in the first Brillouin zone which is below the TM slab dispersion curve. Subsequently, we performed an optimization of the PhC waveguide design to maximize the usable frequency bandwidth below the vertical slab TM waveguide mode. The optimization consisted of an extensive parameter sweep of the following parameters: radius of the holes \( r \), and lateral shifts of the holes in the first \(( sy_1) \) and second row \(( sy_2) \). This resulted in a relatively small radius \( r = 0.25a \), and hole shifts of \( sy_1 = 0.02a \) and \( sy_2 = 0.07a \) in outward direction with respect to the center of the PhC waveguide.

A further improvement of the usable low loss frequency bandwidth PhC waveguide can be achieved by increasing the thickness of the core layer \( t_{\text{core}} \). However, if the vertical cross-section of the PhC waveguide becomes too large, higher order modes may be able to propagate. It is still not completely clear how a hard criterion can be defined to determine the single mode condition of a slab PhC waveguide by using 3D supercell simulations [20]. Therefore, we introduce our own figure of merit based on the confinement factor of the simulated modes. Since we operate the PhC waveguide close to the cutoff of higher order modes, we expect that there is only one mode that has a significantly higher confinement factor than all other modes. Therefore, we use

| \( t_{\text{core}} \) [a] | \( \Delta \omega a/(2\pi c) \) | \( \Delta \lambda \) [nm] | \( \Delta \omega a/(2\pi c) \) | \( \Delta \lambda \) [nm] | MSR* |
|---|---|---|---|---|---|
| 0.5 | 0 | 0 | 0.0110 | 56.7 | 7.54 dB |
| 0.6 | 0 | 0 | 0.0138 | 77.4 | 6.63 dB |
| 0.7 | 0.0002 | 1.2 | 0.0159 | 91.3 | 9.23 dB |
| 0.8 | 0.0038 | 23.3 | 0.0163 | 99.6 | 9.82 dB |
| 0.9 | 0.0046 | 30.9 | 0.0157 | 99.8 | 9.14 dB |
| 1.0 | 0.0067 | 41.3 | 0.0152 | 99.2 | 8.50 dB |

*MSR: confinement ratio defined as the ratio of the percentages of the energy confined to the PhC waveguide core between the first order mode and the next higher order mode.

\( \Delta \lambda \) is determined by evaluating \( \omega a/(2\pi c) \) for the edges \( \omega _a \) of the obtained frequency bands for \( a = 392 \text{ nm} \).
the ratio between the energy overlaps of the first and the second order mode as our figure of merit. We call it mode suppression ratio MSR. Here, a MSR of 10 dB means a by a factor of ten lower confinement factor of the next higher order mode with respect to the fundamental PhC waveguide mode. Table 2 lists the usable frequency bandwidth and the MSR for various core layer thicknesses $t_{\text{core}}$. For all further investigations we used the waveguide having a core layer thickness of $t_{\text{core}} = 0.8a$, because it has the largest MSR and still provides a large usable bandwidth. By scaling the lattice constant $a$, the lowest propagation loss value can be tuned to match the operation wavelength $\lambda_0 = 1550$ nm. A lattice constant $a = 392$ nm is found.

### 4.2. Material and free-carrier absorption

The metallic contact layers and the doped contacting channels in close proximity to the optical mode can result in very large propagation losses. By increasing the channel height $h_{\text{top}}$ the absorption in the metallic contact layer can be reduced, however, this comes with two undesired side effects: First, the thermal and electronic resistances increase with the channel height $h_{\text{top}}$. Second, the holes created by our dry-etching process have a cylindro-conical hole shape rather than the desired cylindrical shape. The angled sidewalls are largely responsible for the losses induced by fabrication imperfections [21]. By increasing the height of the upper part of the contact channel $h_{\text{top}}$, the core layer is shifted towards the conical part of the etched holes resulting in increased scattering loss.

In addition to absorption in the metal contact, free-carrier absorption can be an issue too. The losses due to free-carrier absorption of the highly doped contact channels could be reduced by decreasing the doping concentration or by reducing the channel width $w$. Both measures counteract our effort of providing efficient current injection and an optimization is not performed here. In the following, we estimate the additional propagation loss penalty $\alpha_{\text{abs}}$ originating from free-carrier absorption in the channels and the metallic contact layer as a function of the channel height $h_{\text{top}}$ and the core layer thickness $t_{\text{core}}$. Based on those results, we determine the height of the top contact channel $h_{\text{top}}$ such that propagation losses due to absorption remain below 10 dB/cm. A 2D model approximating the cross-section of the waveguide (cf. left panel of Fig. 5) has been established with Lumerical. The electromagnetic fields located in the ab-

![Fig. 5. Left: A simplified 2D model of the device to estimate the height of the contact channel $h_{\text{top}}$ that minimizes the losses originating from the metallic contact and the doped cladding layers. Right: The propagation losses of the TE mode for $\lambda = 1550$ nm and for four different core layer thicknesses $t_{\text{core}}$ as a function of channel height $h_{\text{top}}$ computed with Lumerical, a commercial mode solver.](image-url)
sorbing layers give rise to absorption losses. Because the transverse field distribution obtained by 3D FDTD simulations is very similar to the field distribution obtained with the approximate 2D model, the absorption losses can be approximated reasonably well by the 2D models. Lumerical is a commercial mode solver based on a finite difference frequency domain method (FDFD) and is capable to simulate the modes of dielectric waveguides including lossy materials. Furthermore, we assume homogeneous carrier distributions in the doped layers and account for free-carrier absorption by using complex refractive indices for $\lambda = 1550$ nm (indicated in Fig. 5 (left), where $p$ and $n$ signify free holes and free electrons, respectively). On the right of Fig. 5 the propagation losses are shown for the TE-mode for various thicknesses $t_{\text{core}}$ as a function of the height $h_{\text{top}}$ of the upper channel. It can be seen, that - for a given target loss value - the height of the top contact channel is smaller for thicker core layer thicknesses $t_{\text{core}}$. For a small propagation loss contribution due to absorption ($\alpha_{\text{abs}} < 10$ dB/cm) we can finally determine a top contact channel height $h_{\text{top}} \approx 500$ nm for a core layer thickness of $t_{\text{core}} = 0.8a = 313$ nm.

5. Design considerations for carrier transport and injection

5.1. Depletion width and surface space charge density of our etching process

The InP dry-etching step for hole formation induces damages on the etched surfaces that manifest themselves by a surface charge density and a depletion zone at the surface boundary. This effect reduces the effective width of the contacting channel usable for current conduction and is one of the main limitations in down-scaling the contact channel width $w$. In a first step, we try to extract realistic numbers of the depletion width and the resistivity of the narrow channels from a simple experiment: Narrow channels have been fabricated by deeply etching trenches into a 1.5 $\mu$m thick InP layer (measured doping concentration $4.5 \times 10^{17}$ cm$^{-3}$, resistivity of the conducting layer is $\rho = 3.24 \times 10^{-3}$ $\Omega$m) grown on a semi-insulating Fe-doped InP substrate. A 3D illustration is shown in Fig. 6(B). Figure 6(A) shows the measured resistance and the conductivity of the etched channels for various channel widths $w$. The smaller the channel width $w$, the higher is the measured resistance. The smallest channel with a width $w = 100$ nm does not allow current conduction. This is due to the fact, that the usable width of the channel for current conduction is reduced by a depletion layer formed at the rough surface resulting from the dry-etching process. The depletion width of our process was found $w_{d} = 56$ nm$\pm3$ nm for a doping of $4.5 \times 10^{17}$ cm$^{-3}$. Thus, the effective contact channel width that can be used for carrier conduction is reduced to $w_{\text{eff}} = w - 2w_{d}$, and accordingly the smallest contact channel with $w = 100$ nm is completely depleted. The smallest channel width $w$ of our experiment allowing for current injection is $w = 200$ nm.

The measured doping concentration of $n = 4.5 \times 10^{17}$ cm$^{-3}$ is rather low for the purpose of pumping an active device with a low series resistance. If we assume a constant surface charge density (approximatively given by the deep etching process only), then a higher doping concentration results in a smaller depletion width $w_{d}$ and simultaneously reduces the resistivity $\rho$. Additionally, the surface charge densities resulting from a wet-etching process (needed for the under-etching) are typically lower than the ones from the dry-etching process. Thus, the here presented parameters for the carrier conduction properties represent a worst-case scenario.

We conclude, that the depletion zone formed by the dry-etching process in this experiment dominates the current conduction properties for channel widths in the order of $w \approx 2w_{d}$. Note, that the largest measured current density for the trench with width $w = 200$ nm is $J = 67$ kA/cm$^2$ and thus we conclude that a contact channel width of $w = 200$ nm (as used in the PhC waveguide design to obtain low propagation losses) is able to conduct typical current densities for lasing devices of $J \approx 0.5 - 5$ kA/cm$^2$. 

#162058 - $15.00 USD  Received 24 Jan 2012; revised 29 Mar 2012; accepted 30 Mar 2012; published 6 Apr 2012  (C) 2012 OSA  9 April 2012 / Vol. 20,  No. 8 / OPTICS EXPRESS  9272
5.2. Gain of the active device

In a next step, we estimate how much current will be necessary to pump the active waveguide to transparency. This, of course, depends on the design of the active gain material. If the active material is composed of quantum wells (QW), the number of wells is a crucial parameter. Therefore we are interested in the number of QWs that minimizes the transparency current density - and in the corresponding current density.

We model the gain $g$ of a single QW with a logarithmic relation $g = g_0 \ln(J/J_0)$, where $g_0$ is the gain coefficient, $J$ is the current density, and $J_0$ is the material transparency current density. In the presence of a number $N$ of QWs, we assume that the current is evenly distributed among the QWs. The gain of $N$ QWs can then be written as

$$g = N g_0 \ln\left(\frac{J}{NJ_0}\right).$$

(2)

In case of a semiconductor optical amplifier (SOA), transparency of the waveguide is reached if $g = \alpha_{WG}$, where $\alpha_{WG}$ are the waveguide losses. The waveguide transparency current density is, therefore, given by

$$J_{tr} = N J_0 e^{\alpha_{WG}/(NJ_0)}.$$  

(3)

We find $N = \alpha_{WG}/g_0$ as the number of QWs that minimizes the waveguide transparency current density. Experimental data of our QWs (7.5 nm InGaAs layers separated by 12 nm InGaAsP barrier layers) yield a gain coefficient of $g_0 \approx 39$ dB/cm for a single QW. Assuming that $\alpha_{tot} \approx \alpha_{WG} < 20$ dB/cm we find the number of QW minimizing the waveguide transparency density to be $N = 1$. By using Eq. (3) a transparency current of $J_{tr} \approx 2.7 J_0$ is found. The precise value of $J_0$ is hard to determine experimentally if the waveguide loss is not exactly known. For our QW material we estimate it to be $J_0 < 0.2$ kA/cm$^2$. Since only one QW has to be pumped to transparency for a net gain, we can estimate the transparency current to be $J_{tr} < 0.54$ kA/cm$^2$. Similar current densities have been measured in the fabricated trench waveguide based laser devices and the required current conduction can be supplied by the narrow contact channels - provided that the gain of the active device is not degraded by excessive thermal heating.

5.3. Heat conduction

Since the contact channels are surrounded by air, the generated heat can only be conducted and dissipated vertically along the channels and laterally in the core layer. An insufficient heat...
conduction may reduce the gain and prevent the devices from functioning. We thus investigate the steady state heat conduction equation [22, 23] in the channel structure

\[ \nabla (-k \nabla T) = H, \]  

where \( T \) denotes the temperature, \( k \) the thermal conductivity (\( k_{InP} = 0.68 \text{ W cm}^{-1}\text{C}^{-1} \) for \( 300 \text{ K} \)) and \( H \approx P_{\text{ohmic}} + P_{\text{NR}} \) the heat generation rate, which mainly consists of ohmic heating \( (P_{\text{ohmic}} = I^2R, \text{where } R \approx 1 - 10 \Omega \text{ for our device and a doping concentration of } 4.5 \times 10^{17} \text{ cm}^{-3} ) \) and heating due to non-radiative recombination in the active layer \( (P_{\text{NR}} = E_g R_{\text{Auger}} \approx E_g C n^3 \text{ [24]}) \). If we neglect lateral heat conduction in the core layer, then the heat flux is restricted to the \( z \)-axis and we can solve the 1D heat equation. We assume a maximum height of both channels of \( h_{\text{total}} \), heat sinks with constant temperature \( T_{\text{sink}} \) at the end of the channels (InP substrate and metal contact), and an evenly distributed heat generation rate \( H \). We obtain for the temperature distribution \( T(z) \) along the channels

\[ T(z) = -\frac{H}{2k} z(z - h_{\text{total}}) + T_{\text{sink}}. \]  

Thus a maximum temperature \( T(h_{\text{total}}/2) \approx 44^\circ \text{C} \) results for the center of the 1D channel if \( h_{\text{total}} = 4 \mu m, J = 1 \text{ kA/cm}^2, \rho = 3.24 \times 10^5 \Omega m \) for a doping concentration of \( 4.5 \times 10^{17} \text{ cm}^{-3} \), an active device length \( L_{\text{device}} = 500 \mu m \) and \( T_{\text{sink}} = 20^\circ \text{C} \) are used. The moderate temperature increase of \( 24^\circ \text{C} \) in the waveguide core is mainly due to non-radiative recombination and meets the expectations of a standard diode laser. We thus conclude, that the narrow contact channels - although surrounded by air - provide sufficient heat conduction for an operating active device with waveguide losses \( \alpha_{dB} < 20 \text{ dB/cm} \).

6. Fabrication tolerance for the widths of the contacting channels

The fabrication of the proposed design is challenging. The most critical parameters are the widths \( w \) of the two contacting channels. If we increase \( w \) beyond the 206 nm used so far, then the frequency range of the PhC waveguide mode below the background line is reduced. At a width \( w \approx 310 \text{ nm} \), the PhC waveguide mode is located above the background line, where no low loss behavior is to be expected. Any width smaller than 206 nm enlarges the low loss frequency regime and thus improves the low loss performance of the waveguide. This gives us a notion of the fabrication tolerances. In order to give specific numbers, one would have to specify the required frequency bandwidth and the corresponding loss figure. From an electronic perspective, the minimum width \( w \) of the contacting channels is \( w = 111.7 \text{ nm} \) for a carrier concentration \( n = 4.5 \times 10^{17} \text{ cm}^{-3} \). However, we expect a substantial reduction of the depletion width \( w_d \) and a reduction of the resistivity \( \rho \) of the contacting channels for a doping concentration of the cladding layers in the order of \( n > 10^{18} \text{ cm}^{-3} \). This largely relaxes the constraints on the minimum width \( w \) of the contacting channels. All in all, we expect a good performance if the contacting channel widths are roughly in the range \( 100 \text{ nm} < w < 200 \text{ nm} \). We have promising preliminary results of fabricated structures. An example was already shown in Ref. [16].

7. Conclusion

We presented an active low loss PhC waveguide design with a vertical contacting scheme that promises a net gain for an electrically pumped active in-plane PhC waveguide. The optical performance was determined by a 3D FDTD simulation. A loss figure of of less than 20 dB/cm for a wavelength bandwidth of \( \Delta \lambda = 23.3 \text{ nm} \) was computed. For the electrical performance and the assessment of the waveguides potential for optical gain, a number of approximations...
were necessary to realistically estimate parameters such as material and free-carrier absorption, heat conduction, gain material and optical propagation losses.

Other vertically injected in-plane PhC waveguide lasers reported in literature [1–4] are based on multi-mode PhC waveguide designs (> W4 PhC waveguide). Those devices achieve output powers in the order of a few mW, which is considerably larger than the achieved output powers for membrane based PhC lasers [11, 12]. However, either cavities [2, 4] or constrictions [1] had to be added to the multi-mode PhC waveguide designs to achieve mono-mode operation. Because of the involved resonances, the multi-mode PhC waveguide designs can only be used for lasing and not for broad-band amplification. As opposed to that, our design has the advantage of having a true single mode operation range with low propagation losses. To our knowledge, the proposed design is the first single mode PhC waveguide design with a vertical carrier injection scheme that can be used for the implementation of an electrically pumped broad-band (Δλ ≈ 25–100 nm) semiconductor optical amplifier.