Towards high-density interconnects at 637 nm

Joe A. Smith, Jorge Monroy-Ruz, Pisu Jiang, John G. Rarity, and Krishna C. Balram
QET Labs, Department of Electrical and Electronic Engineering and H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1UB, UK
(Dated: October 1, 2021)

At visible wavelengths, photonic components could be designed at micron-scales to synchronously control time-critical systems. However, compatible photonics platforms have low refractive index contrasts, and so gratings must be physically large for energy to be efficiently refracted. We develop two ideas to address this problem: a second-order grating that sums multiple optical modes to increase its intensity output, and an embedded metal grating that significantly enhances the attainable refractive index contrast. We experimentally evaluate the second device to be the more viable and present results that can be developed to realise efficient photonic interconnects at high density. This would be useful in applications such as cryogenics where space is constrained.

I. INTRODUCTION

Electrical wiring is a bottleneck as cryogenic computational devices scale, with prototype quantum computers interfaced through thousands of wires to higher temperature electronics [1]. Each wire contributes a thermal budget to be offset by the available cooling power. Electrical wiring is a known bottleneck, too, in data centres, owing to its added latency [2]. This will undoubtedly rear its head for quantum information processing as quantum computers evolve into highly modular interconnected cryostats.

In contrast, photonics offers a thermally isolated high-speed route to interconnects [3-4]. Interfaces between silicon photonic circuits and fibre optics have been well developed in the last fifteen years, with some designs experimentally demonstrating less than 1 dB of loss [5]. However, cryogenic photonic chip coupling adds further challenges in spatial and mechanical constraints. For cryogenic microscopes used to characterise solid-state emitters integrated in photonic circuits, grating coupler development has concentrated on small spot size focussed Bragg out-couplers interfaced via lenses [6]. In this case, out-coupling efficiencies of simple few period Bragg structures approach 3 dB [7]. The advantage of matching the waveguide to a diffraction limited spot is that it can be realised at the scale of the waveguide as opposed to requiring large tapers, which take up large areas of the substrate, and hence considerable area of the cryostat. In silicon photonics, a transition between a single moded substrate, and hence considerable area of the cryostat.

In this work, we will explore this trade-off. Firstly, we consider the best-case grating coupler realised by etching dielectric waveguides, considering the low refractive index limitation described. We then explore how this design performs poorly as an efficient in-coupler. Considering bidirectional information exchange, we develop an improved design method and use this to design a bidirectional coupler by burying a metal grating underneath the waveguide layer. The metal breaks the symmetry of the device to create an efficient channel to the interfaced beam above the sample. Both grating couplers presented are compact owing to their micron-sized mode profile and can be fabricated robustly owing to their simple geometry so could be adopted as high-density photonic interconnects.

II. NANOSCALE GRATING DESIGN CONSIDERATIONS

A grating coupler is a periodic structure used to diffract light from a waveguide to free-space or vice-versa with a narrow bandwidth defined by its periodicity [15].
Typically, the grating is realised by etching crenelations into the waveguide, causing periods with lower effective refractive index. Constructive interference due to the index modulation causes light in-plane to change direction and be directed out of the plane. As light is directed out-of-plane, it can be placed at any location on a photonic circuit, which has advantages in routing complex circuits and allows in-situ testing, compared to coupling light from the edge of a substrate. The design period $\Lambda$ of the grating can be found from the Bragg condition: given an integer $m$ corresponding to the Bragg order, a wavelength of interest $\lambda$, the targeted angle of emission $\theta$ through a cladding of index $n_c$ and $n_{\text{eff}}$ the effective refractive index of the etched and unetched dielectric teeth,

$$\Lambda = \frac{m \lambda}{n_{\text{eff}} - n_c \sin \theta}. \quad (1)$$

The effective index is a weighted average between the waveguide refractive index $n_{\text{wg}}$ and the refractive index of the etched region $n_c$, set by the duty cycle $D$,

$$n_{\text{eff}} = D n_{\text{wg}} + (1 - D) n_c. \quad (2)$$

It can be seen that a change in the design period or duty cycle will cause the light to be emitted at a different angle from the structure. Beyond this 1D formula, there is one other key consideration to design a 3D grating coupler: the width and length of the grating should match the size of the optical beam to which it couples. Usually, the grating is around 1 $\mu$m wider than the beam to allow positional tolerance in coupling. It is then necessary to match the width of this grating with the width of the single mode waveguide. This is achieved by tapering, focussing elements, or a combination of both. A taper adiabatically increases the width of the waveguide to the width necessary. A focussing element can be added by curving the gratings around the feed waveguide, creating a lens effect. The curvatures of the gratings are set such that they have a common focal point at the origin of the single mode waveguide [16]. In realising the grating, the smallest feature size achievable sets the level of control of the design. With optical gratings, this means features are necessarily nanoscale to mould the shape of the sub-micron mode of light. Owing to this, high resolution instrumentation and cleanroom processes are required. In this work, electron beam (e-beam) lithography is used in combination with plasma etching and lift-off.

The attainable resolution of the features achieved in lift-off can be high as the process is not limited by plasma chemistry, only by the formation of the resist pattern. Multiple layer lift-off processes can produce features smaller than 10 nm [17]. One disadvantage is that the smoothness and profile cannot be well-tuned unlike chemical etch techniques which is critical for instance in long dielectric waveguides, where scattering losses are significant. A main challenge in performing lift-off is ensuring the sacrificial layer prevents continuity of the deposited film. If the film is attached between the substrate and the top of the resist, due to a too thin or smooth profile resist, lift-off is not possible. Lift-off is critical to the final design in this work. Firstly we consider a plasma-etched dielectric grating following state-of-the art 2nd order Bragg grating designs [7].

### III. MICROSCOPIC OUT-COUPLER

Forming dielectric gratings in silicon nitride on silica brings two significant problems compared to the moderately efficient small diffractive couplers reported in suspended gallium arsenide membranes [7]. Firstly, the silicon nitride has a considerably lower refractive index. Secondly, the silica contrast means that light entering or exiting the grating will preferentially enter the substrate compared to a suspended platform. In addition, to focus at the micron-scale grating from an external point beyond the cryostat and its surrounding heat shielding requires the use of a long working distance objective (6.0 mm MY100X-806 100X Mitutoyo). This long distance reduces the Numerical Aperture (NA) of the available objective to $\text{NA} = 0.7$ or an acceptance angle of 45 degrees. Owing to this, light reflected by the grating coupler will not be collected at large diffraction angles. Here we optimise a “best-case” diffraction-limited grating coupler design within these limitations, using a 270 nm nitrogen-rich silicon nitride film ($n = 1.89$ at 637 nm) [11], with this thickness chosen to maximise refractive index contrast whilst remaining single-moded.
The best-case device is found by varying the duty cycle and design period of the grating \((\Lambda, D)\) over a large parameter space and maximising the far-field projection of the power \(T_{NA}\) in the top monitor that falls within the desired NA, using the particle swarm algorithm in Lumerical FDTD Solutions [18]. Lumerical decomposes the near field data into a set of plane waves propagating at different angles. We integrate the power in the far field of the power parameter space and maximising the far-field projection of the power. The simulations converge with \(T_{NA} = 48.0\%\) for a design accepting angles up to 60° (0.9 NA) or \(T_{NA} = 42.4\%\) accepting angles up to 45° (0.7 NA).

The angular power distribution of the latter design is depicted in Fig 4(a). Here the design parameters are \((\Lambda, D) = (1.41\ \mu m, 0.77)\). It can be seen in this plot that there are four discrete lobes of emission. Most of the energy is confined in the 0.7 NA acceptance angle (shown in orange). These distinct lobes arise from the Bragg condition of the grating which can be observed in Fig 4(b). The 2D cross-section of the grating shows the four emission directions, to be collected by the 0.7 NA lens. The cross-section shows that a large proportion of the optical power leaves the device in these lobes, with some proportion sent to the silica substrate of the device. The \(T_{NA} = 42.4\%\) efficiency is near optimal considering an air suspended SiN structure would have \(T_{above} = 50\%\) and the higher refractive index glass in the bottom plane reduces this. We note a similar study by Zhu et al. to optimise suspended silicon nitride grating couplers for microscopy by finding the period that emits into the first and second order diffraction mode, to maximise the energy collected into an NA = 0.65 objective, although their work does not consider modulating the duty cycle \(D\) [19].

One further consideration to this design is the robustness to errors in the parameters \((\Lambda, D)\) that will occur during fabrication. In Fig 4(c) and 4(d), a local sweep of each parameter examines the tolerance to this design and notes 20 nm accuracy is required in the set period and a 2 % tolerance in the duty cycle to keep the efficiency above 40 %, which are achievable tolerances for fabrication.

Fabrication proceeded by spin-coating a CSAR-62 e-beam resist onto the SiN film. This resist has a plasma etch rate of 1:11 to SiO2, compared to the 1:1 selectivity of PMMA so maintains good contrast for the 270 nm SiN etch depth [20]. The resist was spun-coat for 1 minute at 4000 RPM for 400 nm thickness (confirmed with a Bruker Dektak surface profiler) then softbaked for 1 minute at 150 °C on a hot plate. Silica is prone to charging distortion under e-beam lithography as the substrate does not provide a good return path for the electrons. To prevent this, 20 µl of a thin conductive coating (Allresist Electra 92) was spun-coat on top of the resist (4000 RPM for 40 s) to dissipate charge.

Following these steps, the design was written using the Raith Voyager e-beam with a base dose of 160 µC /cm². The resist was developed in a commercial developer using water as a stopper. Initially, the resist was stopped in deionised water for 30 seconds but this caused cracks to form. Changing the stop time to 15 seconds prevented this. In the etch process SF6 was added to the Inductively Coupled Plasma (ICP) chamber, following the results of Srinivasan [21], who found the ratio of SF6 to fluorocarbons control the verticality/smoothness fraction of the sidewall. ICP etches were performed on an Oxford PlasmaPro Cobra 300. In Fig 2(a), a cross-section of the waveguide confirms that a smooth vertical sidewall is realised from this etch of the silicon nitride film through into the underlying silica.

As the silicon nitride is quite thick, but with small dimension gratings, it appears some of the components of the grating have become slightly delaminated across all the devices which could affect its performance. Fig 2(b) shows a top view of the 77 % duty cycle grating coupler with the silicon nitride in the first grating period appearing slightly delaminated (highlighted in box). The waveguide is clearly realised and defect free in the trenches separating it from the surrounding film. Following these visual inspections, an experimental setup was built to test guiding in the waveguide from one coupler to the other.

A diagram of this test setup is shown in Fig 2(c). Here, the input laser is controlled via the set angle of a piezo mirror which, translated through a 4f-system consisting of...
of a pair of lenses, sets the angle of entry into the objective and hence the position in the cryostat where the sample is mounted. The sample is mounted on a stepper motor stage in the cryostat. A beamsplitter on a flip mount allows white light illumination of the sample such that the device input grating can be aligned with the beam of the laser. The collection path from the output coupler is transmitted 90% through a beamsplitter and focussed onto a camera.

Fig 2(c) shows an image taken with the camera with the laser aligned to the input grating. This image evidences guiding of light through the waveguide structure with the right side coupler displaying multiple output lobes of emission, as expected from the design. There is a large component of light scattered through the substrate from the in-coupler present. This scatter contributes to a poor signal-to-noise and prevent collection of the out-coupler signal into the fibre, precluding quantitative analysis of this design. This is partly because the silicon nitride film around the in-coupler is attached to the out-coupler and supports a slab mode from any scattered light. To alleviate this, a larger trench could be etched to separate the two grating couplers from the surrounding SiN. However, there are also a fundamental problem with the multimode design, which is especially apparent in this low refractive index contrast platform.

Primarily, although the grating is a good out-coupler into several modes, by definition it is a poor in-coupler into a single mode waveguide. In this second order Bragg design, we have increased the amount of light coupled out of the device by collecting power summed from several different spatial modes, at a loss of modal purity. Owing to this, there is a poor mode overlap between a Gaussian beam and the spatial profile of the light that couples out of the device, resulting in large scattering losses. This problem will be compounded when the device is used in a high-density grating array as the noise that occurs due to this scattering will manifest as cross-talk between devices. Owing to this, instead of considering only out-coupling, a better design would equally consider in-coupling. In the next section, an alternative grating device will be designed by considering both directions of information transfer.

IV. BIDIRECTIONAL COUPLER

In typical cryogenic optical systems, the goal is to image the cryogenically-cooled sample, such as a nanoscale quantum emitter. Here, the optics are critically designed to optimise the efficiency of the light collected from the low-light point emitter. One example of this is that a high NA long working distance objective lens is used with its entrance pupil filled by the excitation laser. This mode of operation gives the best microscope resolution as the beam waist \( w_0 \) of the laser at the sample is diffraction-limited by the NA with:

\[
    w_0 \approx \frac{\lambda}{NA},
\]

resulting in a spot size of \( w_0 < 1 \mu m \). However, using this same mode of operation for coupling to nanophotonic interconnects causes two significant issues. Firstly, the beam spot size at the chip surface is sub-micron, which severely limits the number of grating periods that capture the free space beam. Secondly, the beam is tightly focussed, resulting in a conical Gaussian profile with a sharp phase change across the sample plane. This effectively means that the angle of each section of the beam is different, further restricting the mode overlap with a linear grating coupler.

These two factors are not important for out-coupling as, in reverse, the objective acts as a bucket collector for all modes of light within the collection NA. However, it will be important to realise an efficient in-coupled structure. If instead we underfill the objective, we can purposefully increase the beam waist at the sample and reduce the beam focus, resulting in a less critical profile to match with the grating structure. As we see in Fig 3(a), the ratio of the diameter of the beam at the entrance pupil and the exit pupil is geometrically constant.

Using a pair of achromatic doublets, it was possible to underfill the 3 mm entrance pupil using a 1 mm laser spot. At the 6 mm working distance of the objective, this gives a three times increase in the beam at the sample plane. In Fig 3(b), beam profiling of the under-filled cryostat system was carried out by mounting a camera on the sample holder and moving it in the z-plane, and fitting the size of the Gaussian given the known pixel size.
of the camera. From this, the beam waist can be interpolated by modelling the extracted data as a Gaussian beam. As a result, the $1/e^2$ beam waist was measured as 1.2 $\mu$m, a significant increase from the diffraction limited spot but still much smaller than the typical beam waist used in silicon photonics where an SMF 28 fibre has a Mode Field Diameter (MFD) of 10.4 $\mu$m.

The reduction of the beam waist also reduces the conical nature of the input beam as shown in Fig 3(c). As such, the beam will have an angular span of 20° as opposed to 45°. An added benefit is that the reduced 1 mm beam can be traversed over the 3 mm plane of the entrance plane, accessing a specific range of angles in the sample plane. If the beam is positioned off-centre from the entrance pupil, the off-perpendicular input beam would couple to the grating with a higher coupling efficiency by avoiding perpendicular reflection at the grating. However, the beam still has a significant angular component which could be reduced further using more complicated optics.

Rather than limiting the design to the underfilling parameters, we target a linear grating that is 5 $\mu$m wide. This allows for significantly higher grating coupler densities than standard 12 $\mu$m telecommunications grating whilst still coupling to a broad range of free space mode beams. This structure is also wide enough to be tested with SM 630 fibres (MFD of 4.5 $\mu$m), which we can use to decouple the free space optics performance from the performance of the devices under test. With this width grating, we find in Lumerical MODE that a linear taper can efficiently convert the mode with less than 1 dB loss in 15 $\mu$m compared to the 100 $\mu$m required for silicon on insulator at 1550 nm. This small footprint linear grating will be simpler to fabricate than a focussed design.

The length of the grating will be similar in dimension as its width, in order to couple Gaussian inputs, and so will require a low number of periods. To achieve useful low period number gratings without resorting to summing the efficiency of higher order modes, we consider degrees of freedom beyond the 2D silicon nitride film in order to increase the refractive index contrast. This is to ensure that most of the light leaves the structure in the first few periods. As well as the need for a truncated grating length, by symmetry, emission in the top plane can not be greater than emission in the bottom plane in fully etched designs, even for an infinite grating length. Whilst a partial etch into the waveguide breaks this symmetry, this would result in a lower index contrast grating and therefore require an even longer grating length for the power in the waveguide mode to leave the device. One way to achieve a high-contrast broken symmetry design is to use a metallic layer in combination with a dielectric. Gold is highly reflective, with a low real component and high imaginary refractive index (here modelled as $n = 0.12$ and $k = 3.33$ at $\lambda = 637$ nm [28]). As the inset in Fig 4(a) shows, we can break the symmetry of the device by patterning a gold grating before the silicon nitride is deposited. This gold grating strongly perturbs the effective index of the silicon nitride waveguide. In the simulation, we add perturbations in the top of the nitride due to the conformal nature of the silicon nitride film deposition. Simulations evidence that these perturbations have little effect on the device performance. In Fig 4(a), sweeping the thickness of the gold under the waveguide, we find a maximal contrast between the transmission in the top plane and the transmission in the substrate $T_t/T_s = 4$ with a 70 nm-thick gold film. Simulations indicate that optimal contrast is obtained when the gold layer is deposited before the silicon nitride is grown. We believe this is due to the large out of phase component of the metal which acts as a mirror, reflecting light away from the silica interface where it would otherwise be transmitted and lost into the substrate.

With the thickness set, the period of the grating determines the angle with which the power is expelled, as shown in Fig 4(b). We find that an angle of 20° from the substrate minimises the transmission reflected back into the waveguide mode, corresponding to a period of 320 nm. We also vary the duty cycle and find that a duty cycle of 50 % leads to the most efficient grating device. Fig 4(c) shows a 2D cross-section of power leaving this device for this design angle. The cross-section shows that the power dissipates from the grating over approximately 10 $\mu$m, to produce an intensity pattern with a $1/e^2$ radius of 1.5 $\mu$m, mainly arising from the scattering at the first gold grating period. This device clearly sends a much greater proportion of light into the top plane compared to the proportion sent into the substrate in the earlier design in Fig 1(b). Additionally, in contrast to the four different angle lobes seen in the 2D cross-section in the
previous design, the light leaving this device is monodirectional, at 20° from the substrate.

The transition to this single angle emission pattern by this design should also act as an effective in-coupler of single mode beams. As explained earlier, we will experimentally test this device with a SM 630 fibre so simulate this fibre facet in FDTD with a 4.5 μm MFD, angled at 14° in order to inject light into the device refracted through the air interface at 20°. In Fig 5(d) we can see that a high proportion of the power is transmitted into the waveguide mode through the grating device (T = 0.5). This is a promising simulation of a small efficient bidirectional grating coupler which should be fabricated and experimentally verified.

The gold grating was fabricated through lift-off. The grating pattern is written in PMMA with a base dose of 900 μC/cm² and developed in MIBK:IPA 3:1. 70 nm of gold is deposited using a thermal evaporator on the bare substrate, following a 10 second oxygen plasma de-scum to ensure good adhesion. The grating lift-off is performed gently under acetone. 270 nm of PECVD silicon nitride is then deposited on the grating. The waveguide layer connecting the gratings is written in CSAR-62 and the silicon nitride is etched as in the previous device. The grating lines are extended on either side of the taper section such that the silicon nitride layer can be overlaid with a micron tolerance. In Fig 5(a) the lift-off is demonstrated showing the gold lift-off gratings lines overlaid by the silicon nitride waveguide. Here some significant roughness of the grating is seen. The initial device had significant roughness in the metal layer which was resolved by switching from CSAR-62 to the PMMA. An improvement to this process was attempted using a PMMA bilayer process, but it proved difficult to achieve an even undercut on both sides necessary to realise the grating. In contrast, in Fig 5(b), overdeveloping the PMMA before gold deposition results in smoother gold lines, at an increase in the feature size achievable, and hence the duty cycle of the device. In simulation, increasing the duty cycle results in a 10 % drop in efficiency and a 5 nm redshift to 642 nm at the same design angle and period, which should be observed experimentally.

To test the device experimentally, we mount a V-groove fibre array containing 630 PM fibre (OZ Optics) with a polished facet at 14° in a 6-axis mechanical stage (Maple Leaf Photonics). The two gratings are separated at 250 μm spacing to match the V-groove spacing by a bend and linear waveguide section shown in Fig 5(c). One channel is used to excite the grating and one to readout power from the adjacent grating. The wavelength in the excitation channel is controlled using an acousto-optic tunable filter (NKT Photonics).

The visible wavelength laser excitation can be seen in Fig 5(d), a side-on photograph of a device with coupled light also present at the out-coupler. Here the out-coupler (right) is brighter than the in-coupler (left), with much reduced surface scattering compared to the earlier grating design. The scatter is mostly confined to the grating area. Some light is observed scattering along the waveguide path, suggesting that improvement is needed in the waveguide etch. The out-coupled light is then recorded using a Thorlabs power meter. In Fig 5(e), at its design wavelength, the device is observed to have an S21 of -22 dB when the grating is in near contact with the device, indicating around 10 dB loss per coupler assuming lossless waveguiding. The 10 dB per coupler measured is comparable to standard silicon photonics however significantly lower than the simulated 3 dB. This could be due to residual roughness in the grating lines, compounded by the high duty cycle as adjacent gold lines grow close to one another. It was expected that the increase in duty cycle would result in a slight redshift from the 637 nm design, but this measurement is centered at 635 nm. The set angle of the fibre array is imprecise to around 1° degree and this is likely the cause of this small discrepancy. The device is shown to be highly broadband with a 3 dB bandwidth of around 20 nm, as expected from the low number of grating periods used, and so operates well at the design wavelength.

V. CONCLUSIONS

In summary, we have developed two types of visible wavelength grating couplers to address the need for small form factor devices for high density photonic interfaces. In this work, we observed that the 2nd order Bragg grating often used in cryogenic photonics is unsuitable for bidirectional interfaces because it is highly multi-moded, and has a poor overlap with single-moded Gaussian beams. In contrast, the 5 μm wide embedded
metal grating presented performs well for this task, owing to its increased refractive index contrast and high directionality. Silicon nitride photonics can be deposited directly on metal layers when grown using low temperature PECVD as presented here. Mature processes of this kind include the foundry platform developed by IMEC for integration with CMOS imagers [25].

We note in the literature that embedded metal gratings have been considered before. Wang et al. simulated a focused gold and silver grating below a silicon nitride waveguide for detecting dye molecules although they did not consider the metal thickness as a design parameter [26]. Lamy et al. fabricated a gold grating designed at 1550 nm in the centre of a titanium dioxide waveguide where the metal thickness is considered [27].

Our demonstration experimentally realises this type of structure for visible wavelengths and specifically makes the connection between these high-index gratings and realising small form factor interconnects.

Following on from this demonstration, further iterations are required to refine the fabrication process in order to achieve the 3 dB per grating predicted in the device design. Further design work could extend the linear grating to an apodised profile to better match the free-space Gaussian beam. Following this, 2D arrays of gratings should be fabricated to measure inter-channel cross-talk under established telecommunication protocols, as a step towards high-density interconnects for cryogenic information exchange.

Acknowledgements

JAS thanks A. Murray, M. Cryan and D. Sahin for their valuable expertise. JAS and JGR were supported by British Council IL6 (352345416) and EP/M024458/1. JAS and JMR were supported by EP/L015730/1. JMR was supported by CONACYT. KCB acknowledges support from the ERC (SBS 3–5, 758843). Electron beam lithography and film deposition were carried out on equipment purchased through EP/N015126/1.

[1] F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, R. Barends, R. Bialas, S. Boixo, F. G. Brandao, D. A. Buell, et al., Nature 574, 505 (2019).
[2] D. A. Miller, Proceedings of the IEEE 97, 1166 (2009).
[3] F. Lecocq, F. Quinlan, K. Cicak, J. Aumentado, S. Didams, and J. Teufel, Nature 575, 575 (2021).
[4] D. A. Miller, Journal of Lightwave Technology 35, 346 (2017).
[5] Y. Ding, C. Peucheret, H. Ou, and K. Yvind, Optics letters 39, 5348 (2014).
[6] A. Faraon, L. Peucheret, D. Englund, N. Stoltz, P. Petroff, and J. Vuˇckovi´c, Optics express 16, 12154 (2008).
[7] M. Arcari, I. S¨ollner, A. Javadi, S. L. Hansen, S. Mahmoodian, Ji. Liu, H. Thyrestrup, E. H. Lee, Ji. D. Song, S. Stobbe, et al., Physical Review Letters 113, 093603 (2014).
[8] R. Marchetti, C. Lucava, A. Khokhar, X. Chen, I. Cristiani, D. J. Richardson, G. T. Reed, P. Petropoulos, and P. Minzioni, Scientific reports 7, 16670 (2017).
[9] S. Rajbhandari, J. J. McKendry, J. Herrnsdorf, H. Chun, G. Faulkner, H. Haas, I. M. Watson, D. O’Brien, and M. D. Dawson, Semiconductor Science and Technology 32, 023001 (2017).
[10] A. Minotto, P. A. Haigh, L. G. Lukasiewicz, E. Lunedei, D. T. Gryko, I. Darzewski, and F. Cacialli, Light: Science & Applications 9, 1 (2020).
[11] J. Smith, J. Monroy-Ruz, J. G. Rarity, and K. C. Balram, Applied Physics Letters 116, 134001 (2020).
[12] J. T. Choy, J. D. Bradley, P. B. Deotare, I. B. Burgess, C. C. Evans, E. Mazur, and M. Lončar, Optics letters 37, 539 (2012).
[13] W. H. Pernice, C. Xiong, and H. X. Tang, Optics express 20, 12261 (2012).
[14] K. K. Mehta and R. J. Ram, Scientific reports 7, 2019 (2017).
[15] L. Chrostowski and M. Hochberg, Silicon photonics design: from devices to systems (Cambridge University Press, 2015).
[16] R. Waldhäuser, B. Schnabel, P. Dammberg, E.-B. Kley, A. Bräuer, and W. Karthe, Applied optics 36, 9383 (1997).
[17] M. Rommel, B. Nilsen, P. Jedrasik, V. Bonanni, A. Dmitriev, and J. Weis, Microelectronic Engineering 110, 123 (2013).
[18] J. Robinson and Y. Rahmat-Samii, IEEE transactions on antennas and propagation 52, 397 (2004).
[19] Y. Zhu, J. Wang, W. Xie, T. Tian, Y. Li, E. Brainis, Y. Jiao, and D. Van Thourhout, Optics Express 25, 32927 (2017).
[20] S. Thoms and D. S. Macintyre, Journal of Vacuum Science & Technology B, Nanotechnology and Micromachines: Materials, Processing, Measurement, and Phenomena 32, 06FJ01 (2014).
[21] K. Srinivasan, Ph.D. thesis, California Institute of Technology (2006).
[22] A. C. Ribes, Ph.D. thesis, University of Waterloo (1998).
[23] P. B. Johnson and R.-W. Christy, Physical review B 6, 4370 (1972).
[24] F. Van Laere, W. Bogaerts, D. Taillaert, P. Dumon, D. Van Thourhout, and R. Baets, in OFC/NFOEC 2007-2007 Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference (IEEE, 2007), pp. 1–3.
[25] M. Malak, T. Claes, V. Garcia-Munoz, H. K. Tyagi, R. Van Hoof, G. Winderickx, S. Severi, W. Lee, D. Kim, S. Ahn, et al., in 2018 IEEE Micro Electro Mechanical Systems (MEMS) (IEEE, 2018), pp. 735–738.
[26] L. Wang, Y. Wang, and X. Zhang, Optics express 20, 17509 (2012).
[27] M. Lamy, K. Hammami, J. Arocas, C. Finot, and J.-C. Weeber, Optics letters 42, 2778 (2017).