



Three-wave interaction grating coupler with the sub-decibel insertion loss at normal incidence

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High-efficiency optical coupling between fibers or free-space beams and silicon photonic circuits is critical for reducing system-level losses and enabling scalable packaging. Conventional grating couplers typically require illumination off-normal incidence, limiting their compatibility with vertically oriented sources and fibers. We report the design, fabrication in a commercial foundry, and experimental results of high-efficiency, normal incidence grating couplers for silicon photonics. We observe a maximum coupling efficiency of 85.4% (−0.69 dB) with a 1 dB bandwidth of 20 nm at a central wavelength of 1546 nm. These experimental results verify earlier theoretical and simulation results and pave the way for the use of perfectly vertical grating couplers, as an alternative to edge coupling, in silicon photonics applications that are sensitive to input coupling loss. Further, these results enable the use of grating couplers for vertically oriented elements, such as multicore fibers and VCSELs, and address challenges associated with coupling to free space beams. © 2026 Optica Publishing Group under the terms of the [Optica Open Access Publishing Agreement](#)

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1. INTRODUCTION

Silicon photonics is making inroads in optical systems ranging from optical communication [1,2], spectroscopy [3–5], and quantum optics [6,7] to astro-photonics [8–10]. The gold standard for coupling into silicon photonic single-mode waveguides from a free space or standard single-mode optical fiber is edge coupling, which can achieve both high coupling efficiency and large bandwidths [11,12]. However, edge coupling has several drawbacks. It requires additional preparation of the facets of the silicon photonics waveguides and poses challenges to wafer-level testing, requiring specialized equipment [13]. Additionally, in an edge coupling configuration the mode field diameter (MFD) of the integrated waveguide is limited by the thickness of the lower cladding which is typically 2–3 μm thick. As a result, efficient mode matching to edge couplers often requires either complex processing to allow for suspended silicon edge couplers [14] or lens tapered fibers, which are expensive, fragile, and impose strict lateral alignment tolerances when compared to larger MFD single-mode fibers [11,12,15].

Grating couplers provide a solution to many of the challenges associated with edge couplers. Grating couplers may be fabricated anywhere across the surface of a wafer without the need for complex processing. In a grating coupler configuration, the mode is adiabatically tapered within the waveguiding layer such that there are few limitations on the resulting mode field diameter. However, typical single-layer Bragg grating couplers suffer from low-coupling efficiency and low bandwidth [16,17]. Additionally, standard grating couplers are prone to large back reflections when

designed to operate at normal incidence, as is desirable for coupling to vertically oriented devices such as VCSELs and multicore fibers [16–19]. This has led to a focus on the development of grating coupler designs that have high coupling efficiency and high bandwidth, which may operate at normal incidence for certain applications. This work builds on earlier analytical and numerical modeling of high efficiency, normal incidence grating couplers by designing, fabricating in a commercial foundry, and experimentally demonstrating grating couplers with a peak coupling efficiency of 85.4% (−0.69 dB) at normal incidence.

2. MODELING

Typical grating couplers enable coupling between integrated waveguides and fibers by periodically perturbing the waveguide mode via etches along the length of the waveguide. Each of these perturbations acts as a scattering site which results in constructive interference of the scattered light at a particular angle θ . The relation between the geometry of the waveguide, grating, and emission/acceptance angle is given by the grating equation [16]:

$$\frac{2\pi}{\lambda} n_{gr} - \frac{2\pi m}{\Lambda} = k_0 \sin(\theta). \quad (1)$$

Here, λ is the operating wavelength, Λ is the grating period, m is the diffraction order which we typically take to be 1, k_0 is the wavenumber in the cladding, and n_{gr} is the effective index of the grating which is the weighted average of the effective index for

the unperturbed and perturbed waveguide modes over the period of the grating.

The efficiency of such a coupler is then given by the power normalized mode overlap integral of the grating mode and a desired mode [20]. In the case where a grating is being treated as an output coupler, with light injected from the integrated waveguide and emitted toward a fiber, the efficiency is expressed as

$$\eta = \frac{1}{4P_0 P_{fib}} \left| \iint_S E_{grat} \times H_{fib}^* \cdot dS \right|^2. \quad (2)$$

Here, P_0 is the total power entering and leaving the system, P_{fib} is the power in the simulated ideal fiber mode, E_{grat} is the electric field profile emitted from the grating, and H_{fib} is the magnetic field profile of the fiber mode. For coupling to a single-mode fiber at 1550 nm, the desired fiber mode is often taken to be a Gaussian profile with an MFD of 10.4 μm . As a passive optical component, the grating maintains reciprocity and will yield the same efficiency when treated as an input coupler.

It is often useful to consider the coupling efficiency as the product of two figures: the directionality and the mode overlap. Directionality is the ratio of power directed in the intended propagation direction to the total injected power. The mode overlap is a measure of the similarity between the emitted grating field and the desired fiber mode. It has been established [16,20] that a good mode overlap can be achieved in single-layer gratings by apodizing the scattering strength along the length of a grating. This is achieved by varying the width of the etched perturbations systematically. Conversely, the directionality of a single-layer grating faces a limitation. In a single-layer grating where the etch depth matches the thickness of the waveguide layer, vertical symmetry dictates that half of the power be directed downward toward the substrate. Partial etching has been employed to alleviate this limitation. However, on a 220 nm thick SOI platform, this technique has been shown to have an upper limit of 65% coupling efficiency [21,22].

Other methods have been introduced to break the vertical symmetry of the system such as bottom side reflectors (both Bragg [23] and metallic [24]), as well as various material overlays [19,25] and bilayers [26]. Each of these techniques works by introducing at least one new material layer to the system, requiring additional complex processing.

Directionality is particularly challenging for gratings designed to operate at normal incidence. This is a result of strong coupling to higher order ($m > 1$) reflections back into the waveguide [16]. Multi-etch step gratings have been shown [18,27–33] to improve directionality at normal incidence, by introducing multiple scattering sites within a local period. The additional degrees of freedom introduced by multiple scattering sites enable control over the interference between multiple backward scattered waves from a single local period. The same principle holds true for waves scattered toward the substrate. Designing for the simultaneous destructive interference of these losses ensures good directionality.

Prior work [31,32,34–36] has shown that high coupling efficiency at normal incidence can be achieved with as few as two scattering sites per local period; however, it imposes requirements on the geometry of the structure which are challenging to fabricate. Namely, it requires the existence of buried voids beneath the top surface of the silicon waveguide. While this has been demonstrated in practice, it requires the use of an additional polysilicon layer [31,32,35,36]. It has been further demonstrated that these restrictions to device geometry can be overcome by the inclusion of a

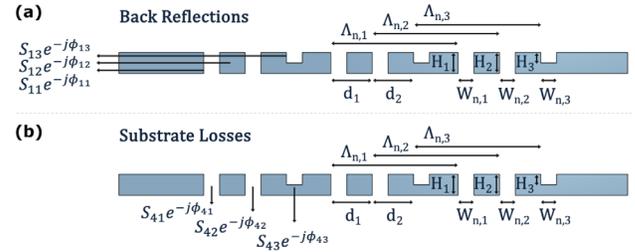


Fig. 1. Generalized geometry of a three-wave interaction grating parameterized by $W_{n,m}$, $\Lambda_{n,m}$, H_m , d_1 , and d_2 . $W_{n,m}$ represents the width of the m th scatterer in the n th local period. $\Lambda_{n,m}$ represents the separation between the m th scatterers in the n and $n + 1$ local periods. H_m is the etch depth of the m th scattering site across all local periods. d_1 and d_2 are initial offset values between the scattering sites in the first local period. Panels (a) and (b) show the back-reflected and downward scattered waves from three scattering sites, respectively.

third scattering site within each local period, as shown in Fig. 1. These three-wave interaction gratings (TWIGs) entirely remove the need for additional material layers without introducing any additional fabrication steps [37].

Here, we use the methods developed in [37] to determine the design parameters of a TWIG coupler optimized for the material stack provided by the commercial foundry Applied Nanotools. We first determine an initial device geometry by applying the analytical solutions to a subset of the TWIG geometry derived in [37]. We then employ adjoint-method-based inverse design to optimize the geometry using our analytical solution as an initial condition. Here, we use the open-source software EMOPT to simulate and optimize the two-dimensional dielectric distribution of the TWIG coupler via FDTD simulations. Two-dimensional FDTDs are sufficient to approximate a three-dimensional grating coupler of sufficient width in the out-of-plane dimension. Within the optimization, we will enforce certain conditions on the figure of merit (FOM) such that we balance the trade-offs between coupling efficiency, bandwidth, and fabricability.

The specific subset of geometries solved for in [37] sets $\Lambda_{n,1} = \Lambda_{n,2} = \Lambda_{n,3} = \Lambda$ and $W_{n,1} = W_{n,2} = W_{n,3} = W$, where $W = (1 - D)\Lambda$ for all n , defining a uniform TWIG grating. Here, $D \in [0, 1]$ is the ratio of a local period that is not etched. Under these conditions, the grating equation may be rewritten as

$$\Lambda = \frac{m\lambda}{(1 - D)(n_1 + n_2 + n_3) + (3D - 2)n_w - n_0 \sin(\theta)}, \quad (3)$$

where n_1 , n_2 , and n_3 represent the effective index in the etched regions with etch depths H_1 , H_2 , and H_3 , respectively, n_w represents the effective index of the unperturbed waveguide, and n_0 represents the index of the cladding material. By adjusting the periodicity Λ , the gratings may be designed for arbitrary emission/acceptance angles θ . In order to achieve coupling at normal incidence ($\theta = 0$) we must impose phase matching conditions to ensure destructive interference between the back reflections of each scattering site within a local period. The necessary widths d_1 and d_2 are found by Eqs. (4) and (5), respectively, where ϕ_{ij} denotes the relative phase difference between back-reflected waves from scattering sites i and j [37]:

$$d_1 = \frac{(\phi_{12})\lambda}{4\pi n_w} + \Lambda(1 - D) \left(1 - \frac{n_1}{n_w} \right), \quad (4)$$

Table 1. Initial Conditions for Optimization

Λ	D	H_1	H_2	H_3	d_1	d_2
637 nm	85%	220 nm	220 nm	70 nm	194 nm	246 nm

$$d_2 = \frac{((\phi_{13} - \phi_{12})) \lambda}{4\pi n_w} + \Lambda (1 - D) \left(1 - \frac{n_2}{n_w}\right). \quad (5)$$

Together Eqs. (3), (4), and (5) completely parameterize the geometry of a TWIG coupler of a given material stack with selected etch depths H_1 , H_2 , and H_3 . The material stack available to us for this work uses a 725 μm thick silicon handle wafer with a 2 μm thick thermally grown buried oxide layer. The silicon waveguide layer is a standard 220 nm thick device layer. An additional 2.5 μm of oxide cladding is deposited above the waveguide layer following patterning. For the etch depths we have selected $H_1 = H_2 = 220$ nm. We have set these two depths equal such that they can be realized in the same process step and minimize the number of lithography steps needed. We have decided to fully etch through the waveguiding layer to remove any possibility of an over-etching error. The third scattering site is assigned a partial etch depth of $H_3 = 70$ nm. It must be noted that these etch depths were assigned somewhat arbitrarily and that the TWIG geometry can accommodate any number combinations for etch depths [37].

The parameters used as the initial condition for the inverse design of this TWIG coupler are given in Table 1. Prior to optimization, we assume that each local period of the grating is identical, such that there is no apodization.

3. OPTIMIZATION

The fully arbitrary TWIG geometry is described by $3N$ local periodicities, $3N$ etch widths, and three global height parameters, where N is the number of local periods. In the devices designed in this work $N = 24$. Optimization of such devices requires fine-tuning in a parameter space that is nearly 150 dimensions. Adjoint-method-based optimization allows us to efficiently navigate the parameter space by calculating the gradient of the FOM relative to each parameter using a single forward and backward simulation [34,38]. By using the geometry described above as an initialization for our optimization, we can reduce the likelihood of converging on a false local optimum.

To ensure a reasonable balance between bandwidth and coupling efficiency, the figure of merit is defined as the average coupling efficiency over several wavelengths of interest. We have

chosen to discretize the FOM over only a few wavelengths of interest to reduce the computational load of each iteration in the optimization. Prior work has shown that the method is effective at improving bandwidth with small impact to the peak coupling efficiency [37]. Additionally, we impose two design restrictions with regards to the minimum feature size of the TWIG coupler based on the tolerances provided by Applied Nanotools. It is enforced that all features with a full etch depth of 220 nm have a minimum critical dimension (etch width) of 70 nm and that all features with a partial etch depth of 70 nm have a minimum critical dimension of 160 nm. These restrictions are enforced during the optimization via a penalty term appended to the FOM.

The FOM for the optimization is given by expression (6), where η is given by Eq. (2), Q is the total number of wavelengths of interest, λ_q denotes the specific wavelength of interest, and $p(\vec{x})$ is a penalty term as a function of the geometric parameters \vec{x} :

$$\text{FOM} = \sum_{q=1}^Q [\eta(\lambda_q) - p(\vec{x})]. \quad (6)$$

The penalty term is implemented through an approximation of the rectangular function given by

$$p(\vec{x}) = A \left(\frac{1}{1 + e^{-k\vec{x}}} + y_0 \right), \quad (7)$$

where A is the scale of the penalty term, k determines the steepness of the roll-off, and y_0 is the cut-off of the rectangular function which is set by the minimum feature size. The optimization is performed over three separate stages with increasing severity and steepness to the penalty term. This is done to enable a wide search of the parameter space before narrowing around a local optimum. Following the completion of all three stages, we predict a peak coupling efficiency of 91% for the fundamental quasi-TE mode of the silicon waveguide. For this device, we simulate a 1 dB bandwidth of 34 nm spanning from 1530 to 1564 nm covering nearly the entire c-band. The performance and geometry of the optimized grating are given in Fig. 2.

It can be seen that several of the local periods of the optimized design share similarities with designs discussed in [18], which investigates blazed gratings employing a nanopillar and L-shaped structure. It is the case that such a geometry is a subset of the TWIG coupler which requires that the partially etched sections overlap with the fully etched sections. Here, we solve and optimize a more generalized geometry, allowing for more degrees of freedom

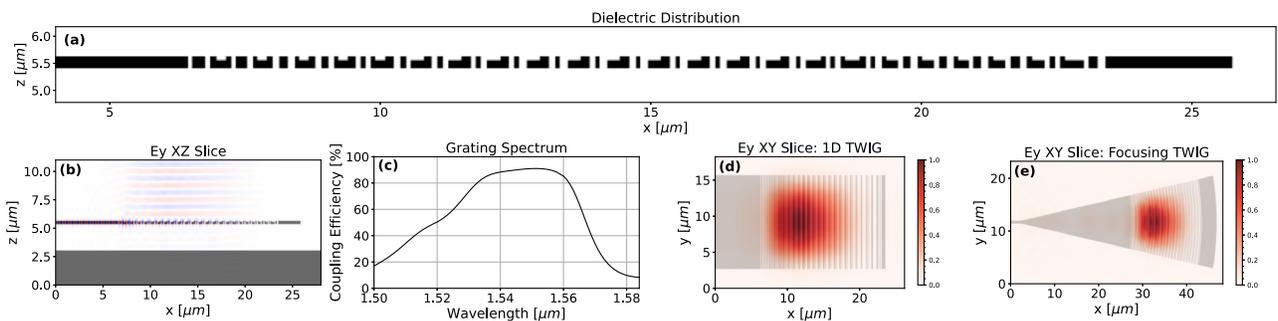


Fig. 2. Simulation results of TWIG coupler optimization. (a) Optimized geometry demonstrating apodization of the etch widths to produce a Gaussian mode profile. The background index here is associated with silicon dioxide (1.444). (b) Electric field profile associated with the quasi-TE mode of the grating. The output is directed perfectly vertical with minimal back reflections and substrate losses. (c) Coupling spectra of the optimized coupler with a peak efficiency of 91% and a 1 dB bandwidth of 34 nm spanning the c-band. Field profiles generated by (d) one-dimensional and (e) focusing TWIG couplers.

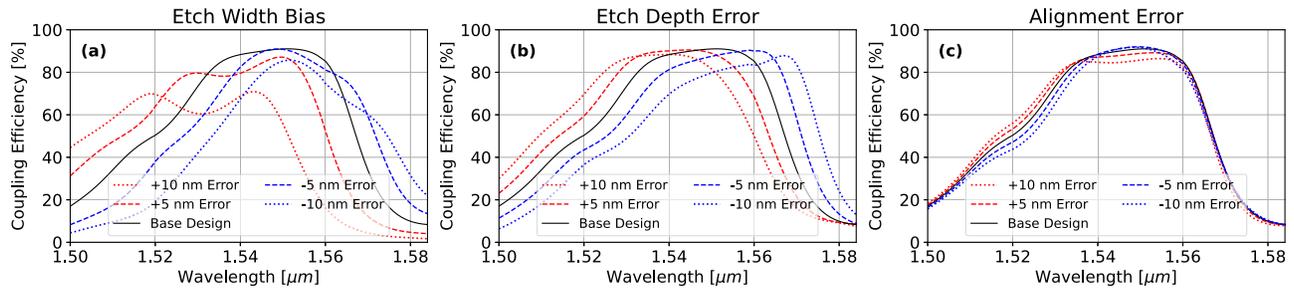


Fig. 3. Simulated impact of fabrication variations for (a) an etch width bias, (b) an etch depth error of the partially etched scattering sites, and (c) the lateral alignment error between the partially and fully etched scattering sites. The etch width bias results in a reduction to the peak efficiency, a shift in the center wavelength, and for positive bias a broadening of the spectrum of a TWIG coupler. The dominant effect of an etch depth error is a shift in the central wavelength. These optimized devices are robust to alignment error and experience little effect over a wide range of errors.

with which to satisfy the phase matching conditions for high directionality.

From this optimized design, we generate two variations of the TWIG coupler: a one-dimensional grating that only varies along the direction of propagation and a two-dimensional focusing grating coupler. The one-dimensional grating coupler maintains a constant width of $13\ \mu\text{m}$ over the length of the grating and employs a $150\ \mu\text{m}$ long adiabatic taper to transition between the width of the grating and a single-mode waveguide. The two-dimensional grating coupler varies radially, introducing a curved phase profile which focuses the coupled light to a single-mode waveguide at the origin of the radial etches [16]. The radial etches span an angle of 22° and begin after an initial offset of $24.35\ \mu\text{m}$ in order to achieve an approximate $10.4\ \mu\text{m}$ MFD. The two-dimensional focusing coupler reduces the length required to transition from the grating mode to a single-mode waveguide. The required footprint of the focusing TWIG is $41\ \mu\text{m} \times 16\ \mu\text{m}$, while the one-dimensional grating requires a footprint of $150\ \mu\text{m} \times 13\ \mu\text{m}$. Figures 2(d) and 2(e) shows the two geometries with the simulated grating modes overlaid.

4. SIMULATED FABRICATION TOLERANCE

Variations in the fabrication process lead to inconsistencies between the designed device geometry and the final device. Here, we investigate the impact of three different types of fabrication variation on the performance of our optimized grating couplers: etch width bias, etch depth error, and lateral alignment error between the lithography steps defining the partially etched scattering sites and fully etched scattering sites. For simplicity, the etch width bias is treated as a constant dilation or shrinking for each scattering site in the grating region. The etch depth error is investigated by slightly adjusting the depth of the partial etch layer H_3 , while it is assumed that a full etch of $220\ \text{nm}$ can be reliably achieved. The alignment error is introduced by shifting all of the partially etched scattering sites together relative to the fully etched scattering sites.

FDTD simulations of the etch width bias reveal that errors on the order of $\pm 10\ \text{nm}$ have a significant impact on the coupling spectrum of the device, both in terms of the peak coupling efficiency and bandwidth. We observe that for a positive etch width bias (over-etch) the spectrum is broadened and shifted toward shorter wavelengths, while the peak efficiency is reduced. A negative bias (under-etch) narrows the spectrum while shifting it toward longer wavelengths and again reducing the peak efficiency.

We observe an offset in the depth of the partially etched layer introduces a shift of the central wavelength while having only a small impact on the peak coupling efficiency and bandwidth. Increasing the etch depth shifts the spectrum toward shorter wavelengths, while reducing the etch depth shifts the spectrum toward longer wavelengths. We observe that alignment errors on the scale of $\pm 10\ \text{nm}$ have very little impact on the device efficiency, bandwidth, or central wavelength. Figure 3 displays the expected impact of each type of fabrication variability on the optimized grating structure.

5. EXPERIMENTAL RESULTS

The devices described above were submitted to the commercial foundry Applied Nanotools for fabrication. Applied Nanotools employs electron beam lithography to reliably achieve feature sizes down to $70\ \text{nm}$, ideal for low volume applications. As these designs require feature sizes below $100\ \text{nm}$, they are not compatible with the $193\ \text{nm}$ process node typically used for integrated photonics multi-project wafer runs. However, increasingly advanced optical lithography is being pursued for integrated photonic applications, reducing the minimum feature sizes provided by commercial foundries. Figure 4 shows SEM micrographs of the fabricated couplers.

Our test structures consist of an input TWIG coupler, a straight single-mode waveguide, $500\ \text{nm} \times 220\ \text{nm}$, with a length of $1.03\ \text{cm}$, and an identical TWIG coupler rotated 180° to act as an output coupler. We use an HP81680A tunable laser which operates in and around the c-band as our input source. The laser is fiber coupled to a polarization maintaining circulator, which enables us to monitor back reflections from the structure. The output of the circulator is coupled to the chip using a polarization maintaining fiber that has been cleaved and is held within a brass ferrule. The brass ferrule itself is held within a rotatable mount enabling us to tune the input polarization relative to the TWIG coupler. A

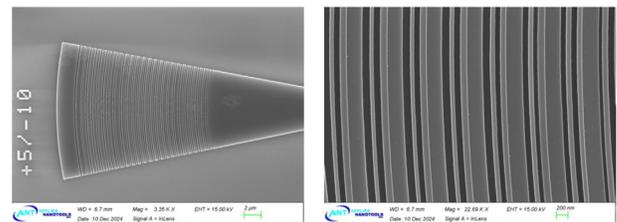


Fig. 4. SEM images of the focusing TWIG coupler provided by Applied Nanotools.

cleaved SMF28 fiber is used at the output coupler before detection at an HP81531A photodiode. Alignment of the input and output fibers is managed by separate Thorlabs Nanomax 600 series 6 axis stages. Additionally, an index matching fluid ($n = 1.444$) has been used here to alleviate Fresnel reflections between the cladding/air and fiber/air interfaces.

To account for possible fabrication errors, we have generated an array of TWIG couplers where each device in the array is designed to compensate for an alignment error, an etch width bias, or a combination of the two. An array of 15 devices is generated for each of the two variations accounting for etch width biases of scale 0 nm, ± 5 nm, ± 10 nm, as well as alignment errors of scale 0 nm and ± 10 nm. Compensating for variations in etch depth would require re-optimization of the grating designs and as such we have elected not to include this process variation in our array.

To extract the efficiency of each TWIG coupler from an optical transmission measurement, we must first account for the propagation losses associated with the single-mode waveguide. The experimental coupling efficiency is given by the function below, where P_{out} is the detected power, P_{in} is the input power, and T_{wg} is the transmission efficiency of the waveguide:

$$\eta_{GC} = \sqrt{\frac{P_{out}}{P_{in} T_{wg}}} \quad (8)$$

We have estimated the propagation losses of our single-mode waveguides from the Fabry–Perot resonances observed during the measurement of the highest performing one-dimensional TWIG coupler [39,40]. The Fabry–Perot resonances observed are a result of weak back reflections at the waveguide/coupler interface. The measured transmission spectrum is given in Fig. 5(a), where a maximum transmission of 47.8% is observed at a wavelength of 1555.5 nm. The free spectral range of the Fabry–Perot resonance is 0.029 nm, which corresponds to a cavity length of 1.03 cm, the separation between the two gratings.

The measured reflection spectrum is given in Fig. 5(b) exhibiting a complimentary Fabry–Perot resonance with a similar free spectral range. At short wavelengths, we observe minimal back reflections on the order of -20 dB which increase sharply as the wavelength increases beyond 1560 nm. The measured back reflections around the peak coupling wavelength are observed to fluctuate between 0.1% and 4.5%. This is of similar order of magnitude to back reflections measured for other techniques used to reduce reflections in perfectly vertical grating couplers [41]. In this work, back reflections were not considered in the FOM used for optimization. In future work, the FOM may be adjusted to explicitly minimize back reflections albeit with some trade-off to the peak coupling efficiency.

To estimate the propagation losses, we perform a fitting of the measured transmission spectra to the analytical solution of a Fabry–Perot cavity with propagation losses. Within this fitting, the power reflectivity of the gratings is left as a fitting parameter. The optimal fitting parameters suggest a propagation loss of -1.35 dB/cm and a power reflectivity of 4.35%, which are in good agreement with the average value reported by Applied Nanotools (-1.2 dB/cm) and the measured back reflections.

According to Eq. (8), from these results, we calculate the peak coupling efficiency of the one-dimensional TWIG coupler to be 81.1% (-0.91 dB) at a central wavelength of 1555.5 nm. The measured 1 dB bandwidth is 20 nm for this device. Similar measurements of the highest performing focusing TWIG coupler

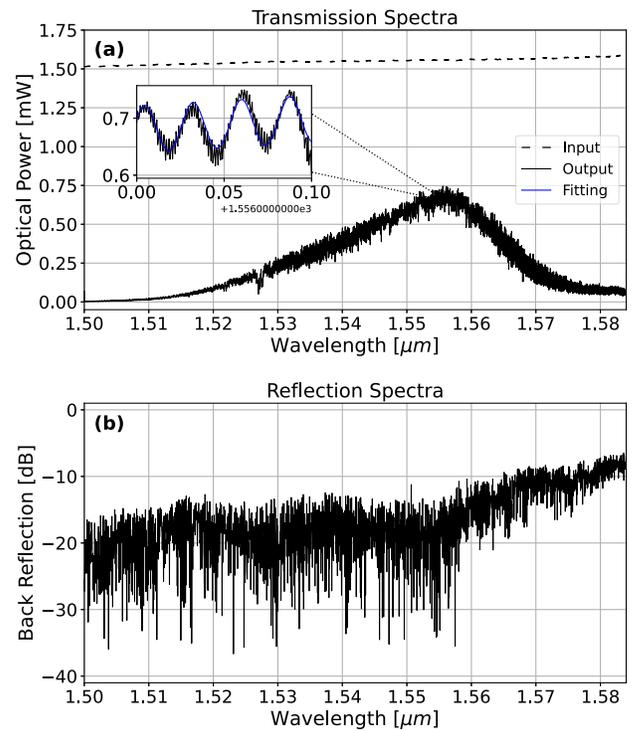


Fig. 5. (a) Transmission and (b) reflection spectra of the highest performing one-dimensional TWIG coupler. A waveguide propagation loss of -1.35 dB/cm is estimated from an analysis of the Fabry–Perot resonances.

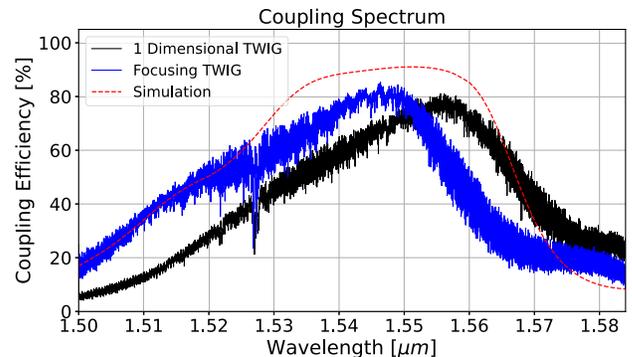


Fig. 6. Experimental coupling efficiency of the highest performing one-dimensional and focusing TWIG couplers, each exhibiting sub-decibel insertion losses.

reveal a peak coupling efficiency of 85.4% (-0.69 dB) at a center wavelength of 1546.4 nm. We find a similar 1 dB bandwidth of 20 nm for the highest performing focusing TWIG coupler. The spectrum of each of these devices is plotted in Fig. 6 along with their simulated performance. We observe that there is a reduction of the peak efficiency and bandwidth of both devices compared to simulated values; however, there is good agreement overall with the expected performance.

Both devices exhibit an abrupt decrease in performance around 1528 nm. We believe this to be a measurement artifact associated with our testing station. This is indicated by the observation that each structure exhibits a similar drop at the same wavelength, 1528 nm, regardless of the shift to the peak coupling wavelength.

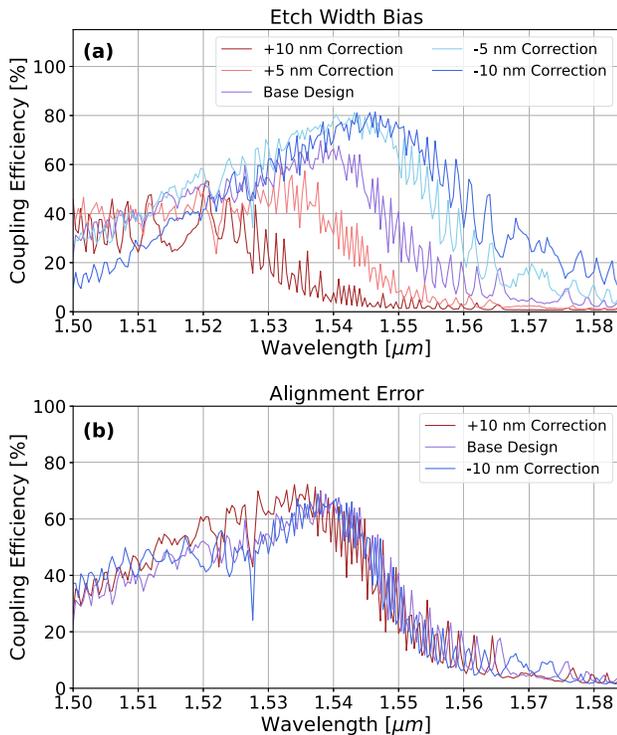


Fig. 7. Experimental coupling efficiency of focusing TWIG couplers demonstrating the impact of (a) an etch width bias in the absence of the alignment error and (b) the alignment error in the absence of an etch width bias.

The one-dimensional TWIG coupler plotted in Fig. 6 has been designed with a -5 nm etch width bias such that it compensates for a 5 nm over-etch. Additionally, this device has been designed for a -10 nm alignment error correction. The highest performing focusing TWIG coupler has been designed with a -10 nm etch width bias correction and a -10 nm alignment error. The difference in the etch width bias between these two highest performing devices may be a result of local etch rate variations caused by the difference in geometry.

Figure 7 shows the measured coupling spectra of several of the remaining focusing TWIG couplers, displaying the impact of each type of fabrication variation. The wavelength resolution of the sweep here has been reduced for the convenience of viewing the closely overlapping measurements. We see good agreement between the experimental data and simulation with regard to both types of fabrication errors. We can see from Fig. 7(a) that a positive etch width bias causes the spectra to broaden and shift toward shorter wavelengths while reducing peak coupling efficiency. We observe that a -10 nm correction exhibits the best performance among the devices with no overlap error. This indicates that the true etch width bias is close to -10 nm. From Fig. 7(b) we can see that, regardless of the alignment error, each of the devices performs similarly, demonstrating robustness to this type of fabrication variation.

Figure 8(a) provides the measured back reflection spectra that result from an etch width bias in the absence of alignment errors. We observe an identical trend to that of the coupling efficiency. A positive etch width bias results in an increase in the measured back reflection intensity as well as a blue-shift of the center wavelength. Figure 8(b) displays the measured back reflection that results from alignment errors in the absence of etch width bias corrections. We

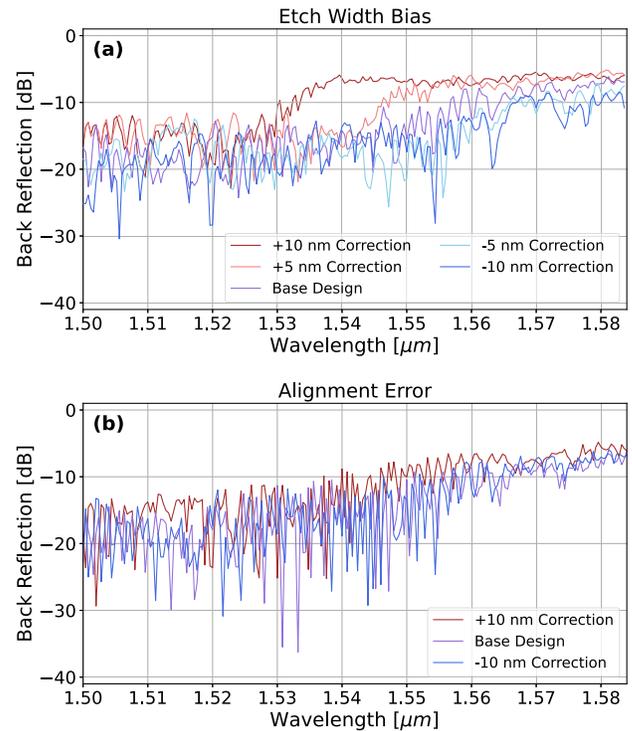


Fig. 8. Experimental reflection spectra of focusing TWIG couplers demonstrating the impact of (a) an etch width bias in the absence of the alignment error and (b) the alignment error in the absence of an etch width bias.

similarly observe that the measured back reflection varies little for alignment errors on the order of ± 10 nm.

For potential etch width errors spanning ± 10 nm, we observe that the peak wavelength shifts by approximately 30 nm, and the peak coupling efficiency is reduced from 85% to 50% . For the same range of errors, the measured back reflections undergo a similar shift. For a $+10$ nm etch width bias, we observe back reflections as high as -20% (-7 dB) for wavelengths longer than 1540 nm. The observed phenomenon is likely caused by the gradual violation of the phase matching conditions required for high directionality [37]. These results suggest fairly stringent tolerances with regard to an etch width bias; however, we observe that the device is robust to variations in the alignment between the full etch and partial etch steps. In future work, additional terms may be appended to the FOM to reduce the variability of device performance with respect to the etch width bias.

6. CONCLUSION

We have designed, fabricated, via the commercial foundry Applied Nanotools, and experimentally validated the performance of high-efficiency grating couplers operating at normal incidence. By applying the principles of three-wave interaction gratings, we are able to optimize for the destructive interference of the typical loss mechanisms challenging perfectly vertical grating couplers: back reflections and substrate losses. Through careful design of the figure of merit we are able to balance the trade-offs between peak efficiency, bandwidth, and fabrication limitations. Our optimized designs predict a peak coupling efficiency of 91% with a 1 dB bandwidth of 34 nm spanning nearly the full C-band. From these

designs we generate a one-dimensional TWIG coupler with a footprint of $150\ \mu\text{m} \times 13\ \mu\text{m}$ and a focusing TWIG coupler with a reduced footprint of $41\ \mu\text{m} \times 16\ \mu\text{m}$. We measure peak coupling efficiencies of 81.1% ($-0.91\ \text{dB}$) and 85.4% ($-0.69\ \text{dB}$) for the one-dimensional and focusing devices, respectively, and 20 nm 1 dB bandwidth for both devices. To the best of our knowledge, these results represent the highest coupling efficiency for grating couplers designed in a standard 220 nm SOI platform, operating at normal incidence without the use of additional material layers such as bottom side reflectors or material overlays.

Adoption of these devices will benefit a wide range of applications of integrated photonics spanning the fields of optical communication, non-linear optics, spectroscopy, quantum optics, and astro-photonics. These devices offer a practical alternative to edge couplers in applications that are sensitive to insertion loss with the additional benefits associated with grating couplers: wider lateral alignment tolerance, convenient wafer-level testing, and flexible placement across the surface of a wafer. Operation at normal incidence enables coupling to vertically oriented components such as VCSEL and multicore fibers, both of which will play important roles in the scaling of optical interconnects. Extension of this method into new material platforms, wavelength ranges, and beam profiles provides a pathway to efficient coupling between any integrated photonic waveguides and fibers or free-space systems.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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