In this work, we present the design, fabrication, and testing of inverse-designed photonic couplers for use in gallium arsenide photonics. The couplers are designed to couple quantum emitters, such as indium arsenide quantum dots, into single-mode optical fibers. The inverse design optimization protocol allows for the exploration of a wide range of feature sizes, which is important for comparing the performance of different designs. We fabricated at least 4 instances of devices following 11 different designs and compared their transmission efficiency to the traditional grating outcoupler. The inverse-designed structures outperformed the traditional grating outcoupler in a single-mode optical fiber optical setup. The use of broadband optimization criteria did not result in statically significant improvement in actual bandwidth, but did decrease the variance in the measured bandwidth, suggesting a more robust design.

**KEYWORDS:** photonics, inverse design, gallium arsenide photonics, couplers

**INTRODUCTION**

There is great interest in the development of on-chip quantum photonic platforms because they offer a potential path toward scaling to a large number of qubits while preserving the advantages of using photons for state initialization, manipulation, or readout. Some examples of photonic elements that would likely be included in such on-chip quantum photonic devices include cavities that can mediate strong coupling to matter-based qubits, demultiplexers, and out-couplers. III–V materials such as gallium arsenide (GaAs) are particularly appealing for quantum photonics because the materials are well-established in optoelectronics, there has been extensive development of methods for fabricating many of the desired photonic devices, and they provide the opportunity to incorporate indium arsenide (InAs) quantum dots (QD) and quantum dot molecules (QDMs), which have excellent optical qualities, as quantum emitters or the host for spin qubits. The high optical quality of InAs quantum dots in a GaAs matrix have even driven the development of methods for combining them with, for example, silicon (Si) photonic structures to create hybrid quantum photonic platforms. Recently, a variety of more sophisticated design optimization techniques have been employed to improve photonic device performance, including the use of genetic algorithms, semi-analytical approaches, and inverse design. Inverse design (ID), in particular, has enabled the investigation of a wider range of design spaces and has produced devices with extremely small device areas and high performance. However, many fabricated inverse-designed devices perform significantly worse than simulations predict, and this performance gap is usually attributed to problems with a sidewall profile and pattern transfer fidelity. Overcoming these fabrication challenges and comparing the performance of a wide range of inverse-designed devices is complicated by the wide range of feature sizes contained within any inverse design.
etching (so-called “RIE lag”), conventional approaches to fabricating inverse-designed devices must be individually optimized for each design. It therefore becomes challenging to determine whether variations in performance between different inverse-designed devices should be attributed to the design or to the degree of process optimization.

Here we report the design, fabrication, and characterization of inverse-designed photonic components tailored for a III–V heterostructure and compatible with single QD or QDM quantum emitters or spin qubits. As an initial proof of concept, we focus specifically on the couplers used to efficiently route light onto and off chip. We first describe the inverse design method we employed to design our devices. We then describe how we employ a novel sleeve and bulk photonic device fabrication method\textsuperscript{24} that allows us to fabricate 11 different inverse-designed devices without any design-specific process optimization. We fabricate and test more than 45 different devices in order to generate statistically valid measurements of their photonic performance. We compare these results to the simulated performance of the designs. We show that the reduction in the minimum fabricable feature size, which is enabled by the new sleeve and bulk method, can be used as a design parameter and enable improvements in both simulated and actual performance.\textsuperscript{25} Finally, we synthesize these results to provide general guidance for the inverse design and fabrication of maximally reliable high-performing devices.

\section*{METHODS}

\textbf{Design.} GaAs quantum photonics are typically conducted in either VCSEL-like pillars (e.g.\textsuperscript{26}) or suspended membranes in which total internal reflection provides z-direction (growth-direction) confinement.\textsuperscript{27} We focus on the suspended membrane approach, which can be more directly extended to on-chip incorporation of waveguides, cavities,\textsuperscript{28} and other photonic device elements. The standard device used to couple light from free space into suspended membrane photonics is a diffraction coupler, as shown in Figure 1a. Such a coupler is analytically designed, with three instances of semicircles that have a quarter wave thickness of both the GaAs (light gray) and air gaps (dark gray). The performance of such a device is most easily understood by considering light propagating in the waveguide and incident on the coupler from the right-hand side. The quarter wave design results in destructive interference that prevents continued propagation of the light. The light consequently scatters vertically out of plane, creating an out-coupler. Light incident on the coupler similarly scatters into the waveguide, thus the same design functions as both an in- and out-coupler. The design wavelength for all the devices we consider here is 960 nm and all reported structures are symmetric in the z-direction. This symmetry necessarily scatters light equally in the +z and −z directions, resulting in a maximum efficiency of 50\% for any coupler design.

Inverse design provides an opportunity to create devices that exceed the performance limits of the traditional diffraction coupler.\textsuperscript{11} This design method explores an orders-of-magnitude larger design space, leading to abstract geometries, such as the example shown in Figure 1b, that can have excellent performance. However, inverse design algorithms must be constrained in two ways. First, the design must be constrained to have no free-floating GaAs zones, as these would not be supported in the membrane. Second, the algorithm must consider fabrication constraints, specifically the minimum feature size that can be reliably fabricated.\textsuperscript{25}

Inverse design of the couplers was performed using the Stanford Photonics Inverse Design software (SPINS).\textsuperscript{29} For the design problem,\textsuperscript{11} a Gaussian beam with a beam waist matched to the measurement optics is vertically incident on a 1.5 × 2.5 μm\textsuperscript{2} design area. Two bars of 200 nm width support the air-clad design. The figure of merit is defined as the fraction of 960 nm incident light coupled into the TE00 mode of the 1.5 μm waveguide. The Gaussian beam was set to impinge 0.75 μm from the right edge of the design region to allow for a larger area to form a reflector;\textsuperscript{30} the linear polarization of the input beam is set to be perpendicular to the waveguide direction of propagation. The optimization included 60 iterations in the continuous phase and 150 iterations in the discrete phase, which includes a fabrication constraint penalty function.\textsuperscript{25}

The work we report here utilizes three families of inverse-designed couplers. Design family D1 uses a minimum feature size of 180 nm, a generic value reliably achievable with e-beam lithography and inductively-coupled plasma etching. Family D2 uses a smaller minimum feature size of 150 nm, which we determined to be reliably achievable with the sleeve and bulk etch method we employed, which is described further below.\textsuperscript{24} Finally, family D3 uses the same 150 nm minimum feature size and incorporates an additional broadband performance optimization constraint by simultaneously optimizing coupling efficiencies for multiple wavelengths centered around the target wavelength.\textsuperscript{31} A small amount of random noise is added to each initial condition on each run, parametrized by initial mean pixel value. The slight difference in initial conditions for the

Figure 1. (a) Traditional coupler with three layers of quarter wave arches and (b) inverse design photonic coupler. Both couplers are coupled to a waveguide heading toward the right; the waveguide for the grating coupler is narrower in width in order to better match the much smaller mode to which it couples.
same problem specification can lead to different final designs, allowing for multiple unique designs in each design family. In the Results and Discussion section, we compare the experimental performance of fabricated devices from each family to their computationally predicted performance.

Fabrication. The traditional method for fabricating photonic components such as the diffraction coupler is soft-mask fabrication via chlorine-based inductively coupled plasma reactive ion etching (ICP-RIE). This fabrication method typically seeks to improve performance by using a multistep etch process with etch conditions in each step optimized for specific feature sizes such as the grating spacing or photonic crystal cylinder radii. ID devices cannot be easily broken into “small” and “large” features and, moreover, include frequent smooth transitions between the “small” and “large” regimes. As a result, fabrication of ID devices with the traditional fabrication methods suffers from RIE lag that causes both pattern transfer fidelity and sidewall profile to become a function of local feature size. These variations are likely the dominant factor limiting performance of ID devices fabricated with traditional methods.

To overcome the challenges inherent to the traditional fabrication process and realize high quality inverse designed photonic components, we developed a sleeve and bulk fabrication process. A prerequisite for this method to work is that the final device must be a suspended membrane such that the fabrication can tolerate variable etch depths. This is not a significant limitation for GaAs or many other material platforms in which membranes are routinely used to provide total internal reflection along the material growth direction. Briefly, this sleeve and bulk method entails three sequential soft-mask fabrication techniques. First, E-beam lithography (EBL), metal deposition, and lift-off are used to produce gold alignment markers that are used to align the two subsequent etch masks. Second, EBL lithography and the “sleeve” etch, shown in Figure 2a,d, define a thin ~100 nm sleeve that follows the perimeter of the etched features (see details in ref 24). This sleeve has a consistent width, circumventing the problems with RIE lag and obtaining both good sidewall verticality and good pattern transfer fidelity. Third, EBL and a second “bulk” etch, shown in Figure 2b,e, is used to remove the bulk of the etched feature while the resist mask protects the vertical side wall defined in the sleeve etch. Both the sleeve and bulk etches utilize 10 sccm of Ar, 15 sccm of BCl3, chamber pressure of 6 mTorr, ICP coil power of 500 W, and a bias power of 25 W. The etch time for the sleeve etch was 2 min and 40 s, and the etch time for the bulk etch was 4 min. Finally, the undercut layer is selectively removed via a 5% HF wet etch, as shown in Figure 2c,f. An optional digital wet etch cleans difficult to remove carbon residuals. A CPD dryer is used to dry the sample without damage due to surface tension on the delicate membrane.

While the sleeve and bulk method allowed us to fabricate all of the ID devices we designed, some devices did not fabricate as well as others. We have identified two common defects that limit fabrication reliability. The first defect occurs when the sleeves on opposite sides of a feature are too close together (i.e., the bulk is too narrow) and the resulting thin section of resist separating these sleeves becomes unstable due to a high aspect ratio (i.e., the resist is too thin and tall and thus falls over). This type of defect can be seen in Figure 3 a) where the unstable resist fell onto the feature in the highlighted region and caused very poor pattern fidelity during etch. The second defect arises as a result of an attempt to avoid the first. In Figure 3 b) we fabricated a feature that we expected would suffer from the resist stability defect. We therefore defined the feature as “all-sleeve,” i.e. we used a slightly wider sleeve width in this local region so that there was no thin bulk between the sleeves. While this improved the fabricability of a few of the ID
devices, it also reduced the sidewall verticality for wider features, as highlighted in Figure 3 b).

Characterization. To characterize the performance of these ID devices we measure the transmission through a coupler-waveguide-coupler device, as shown in Figure 4b. The measurement beam path can be seen in Figure 4a, where light from a “Toptica DLC CTL 950” tunable laser is routed to the in-coupler of the sample. A fraction of the laser light that illuminates the in-coupler couples into the waveguide and then is emitted from the out-coupler at the other end of the waveguide. This can be seen in Figure 4c; the laser is focused, using a NA = 0.42 50× objective, on the in-coupler on the right, and the left (out-)coupler is also bright due to emitted light. The light emitted from the out-coupler is collected by the same focusing objective, and the transmitted intensity is measured using a photodiode. This measured transmitted intensity is normalized to the incident laser power, which is measured on a second photodiode using a 10% fiber-based beam splitter to eliminate artifacts arising from laser power fluctuations. The transmitted intensity is also normalized to reflection from a standard Thorlabs “P01” silver mirror to calculate the absolute transmission efficiency.

The transmission efficiency of the coupler-waveguide-coupler device is measured as a function of laser wavelength between 915 and 980 nm. Example transmission efficiency plots can be seen in Figure 5a,b. The oscillations on sub-nm wavelength scales are an artifact arising from Fabry−Perot interference due to the reflections from the two couplers back into the waveguide. To eliminate this artifact from our subsequent analysis, we apply a 5 nm wide simple rolling average that averages out the Fabry−Perot interference peaks and results in the dashed blue line shown in Figure 5b. We extract the peak transmission efficiency, the peak transmission wavelength, and the bandwidth for ≥90% efficiency, as indicated in Figure 5b. When computing the efficiency of a single coupler from this data, we assume that the two identical couplers in each device have equal efficiency and that the loss from the waveguide is minimal. A comparison between measured transmission and simulated transmission can be seen in Figure 5c. The actual devices achieve a maximum efficiency as high as 86.6% of the simulated maximum.

# RESULTS AND DISCUSSION

We fabricated and tested 11 unique inverse designs, and for each design, 4 devices were measured. These results are presented in Table 1. We compare the performance of the inverse-designed devices to a reference "Grating" device that is of similar size to the inverse-designed devices, is similarly etched completely through the membrane, and similarly couples a waveguide to an optical beam normal to the plane of the material. While more efficient grating devices can be realized by, for example, adding elements that break the symmetry along the material growth direction or increasing the device area, the reference grating we chose provides the most direct comparison for evaluating the improvements that can be achieved as a direct result of using inverse designed devices. For all devices, the peak wavelength, efficiency, and bandwidth report 95% confidence intervals for the corresponding values based on the 5 nm rolling average (see Figure 5b) of four devices. The bandwidth is the 90% (−0.46 dB) bandwidth. Experimental (expt) and theoretical (th) values from the computation design are compared in each instance. The confidence intervals for the experimental data is a 95% confidence interval assuming a t-distribution with a sample size of 4. We also include, as a reference, a particularly well-performing grating outcoupler fabricated by the same methods. All but two ID devices (D1-02 and D1-08) performed at least 50% better than this standard grating vertical coupler. Devices designed using the first inverse design scheme (D1) show a mean coupling efficiency of 17.4%, which is 58.8% of the average computed efficiency for this family of devices (29.6%). The devices designed using the second and third inverse design schemes (D2 and D3) show a mean coupling efficiency of 27.5%, which is over twice the efficiency of the grating vertical coupler (11.2%) and 79.3% of the average computed efficiency for these families of devices (34.7%). We believe the significant improvement in performance for the D2 and D3 families of inverse designs originates in the smaller minimum high index material feature size design constraint that was made possible by the sleeve and bulk process. This conclusion is supported by an increase in both the theoretical and experimental performances. All device designs save D1-02 have efficiency confidence intervals that outperform our grating outcoupler reference. In other words, essentially all the ID devices we tested will reliably outperform a grating coupler even when accounting for the minor variations inevitable in fabrication. Moreover, devices designed to take advantage of the smaller minimum feature size enabled by the sleeve and bulk etch will outperform those that do not.

The bandwidth of the ID devices is approximately equal to that of the standard grating coupler. We note that the transmission efficiency peak was, on average, blue-shifted relative to the design target of 960 nm. This 1–2% blue shift...
was seen in both the theoretical performance and the experimental performance. The blue shift is slightly more pronounced in the theoretical results for design schemes D2 and D3. Despite this blue shift, half of the 44 devices across the 11 inverse designs achieved at least 92% (−0.33 dB) of peak performance at the 960 nm target wavelength. At least two-thirds of the 44 devices across the 11 inverse designs achieved at least 90% (−0.46 dB) of peak performance at the 960 nm target wavelength. This indicates that one can have a high degree of confidence that an ID device will have high efficiency at the design target wavelength. For future designs, we recommend a design target wavelength 1−2% above the actual target wavelength to correct for the blue shift and further improve efficiency at the target wavelength.

The broadband designed devices (D3-11 and D3-12) did not show a statistically significant improvement in the actual bandwidth. However, the D3 devices do show a significant improvement in the device to device variance; (i.e., ±2.9 and 7.7 nm for D3-11 and D3-12, respectively). The mean variance of the two broadband devices tested was estimated to be 25% smaller than that of the mean variance of the other nine inverse designed devices. We believe this indicates that the broadband design criteria improves device robustness to fabrication imperfections.

**Figure 5.** Example transmission measurement data for “D3-11” ID coupler. (a) Transmission curves for four devices. The significant overlap is an indication of the reproducibility between different instances of a nominally identical device. (b) The transmission curve for one device. The dashed line provides a simple rolling average calculated using a 5 nm window. The corresponding peak efficiency, peak wavelength, and 90% efficiency bandwidth are indicated. (c) Transmission curve of single device comparing the (blue) experimental and (green) computationally expected device performance. The actual device peak performance is 86.6% of the computational (theoretical) limit.
Finally, we note that all of the devices fabricated and tested in this study preserve symmetry along the material growth direction, i.e., the etches pass completely through the membrane. As such, their maximum theoretical efficiency for coupling into a single mode normal to the device could never exceed 50%. One of the most important results of the work presented here is that the sleeve and bulk etch process allows for the realization of a wide variety of such inverse designed devices, with efficiencies quite close to their theoretical maxima, without device specific optimization of the fabrication conditions. We are thus able to compare the performance of several different families of inverse designs (D1–D3) without worrying about whether the results are influenced by the degree of device-specific process optimization. There are other families of devices that break symmetry along the material growth direction and could thus achieve theoretical efficiencies of 100%.10 The sleeve and bulk method described here could likely be used to improve the realized efficiencies of such devices, but additional process optimization to control the depth of partial etches would be required.

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table 1. Table of Outcoupler Performance by Device

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