High-efficiency fiber-to-chip interface for aluminum nitride quantum photonics

Mengdi Zhao,1,2 Woraprach Kusolthossakul,1,3 and Kejie Fang1,3,*

1Holonyak Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA
2Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA
3Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA

Integrated nonlinear photonic circuits received rapid development in recent years, providing all-optical functionalities due to photon-photon interaction for classical and quantum applications. A high-efficiency fiber-to-chip interface is key to the use of these integrated nonlinear photonic circuits for quantum information tasks, as photon loss is a major source that weakens many quantum protocols. Here, we demonstrate adiabatic fiber-optic couplers in thin-film aluminum nitride for both telecom and near-visible light, with an efficiency exceeding 80% (55%) for the 1550 nm (780 nm) transverse magnetic-like modes. Our results will facilitate the use of aluminum nitride integrated photonic circuits as efficient quantum resources for generation of entangled photons and squeezed light on microchips.

Nonlinear optics is crucial for realizing key optical quantum resources, including heralded single photons [1] and squeezed light [2, 3], which, however, have heavily relied on using bulk nonlinear crystals since the dawn of (experimental) quantum optics three decades ago. In recent years, development of wafer-scale growth of high-quality nonlinear photonic materials and the associated microfabrication techniques is shifting the paradigm of quantum optics from the conventional bulk crystals to photonic circuits on microchips, driven by the quest of scalable systems and strong light-matter interaction among other potential of chip-scale architectures. Integrated nonlinear photonic platforms now include, for example, silicon [4] and silicon nitride [5–7] with $\chi^{(3)}$ nonlinearity, and more recently aluminum nitride (AlN) [8] and lithium niobate [9, 10] with dominant $\chi^{(2)}$ nonlinearity. The $\chi^{(2)}$ nonlinear materials are particularly useful for generating entangled photon pairs via spontaneous parametric down conversion [11], squeezed light [12], and visible-to-infrared wavelength conversion [13]. With centrosymmetry breaking of the crystal, these materials also possess large linear electro-optic coefficients, leading to applications such as integrated high-speed modulators [14] and microwave-to-optical signal transducers for future quantum networks [15].

A key to the success of these quantum-related applications of integrated nonlinear photonic circuits is a low-loss fiber-to-chip interface, which will help preserving the fidelity of quantum states or increasing success rate of post-selected events to enhance quantum protocols. Typical fiber-to-chip interfaces use, for example, grating couplers and end-fire couplers; however, these coupling schemes generally have substantial insertion losses due to the abrupt mode change. Recently, a new fiber-to-chip coupling method using adiabatic couplers has been demonstrated with robust coupling efficiency exceeding 90% across various material systems, including silicon [16], silicon nitride [17], and diamond [18]. This method uses adiabatic band-crossing between the tapered optical fiber and on-chip waveguide to achieve near-unity optical transmission. Here, we demonstrate such adiabatic fiber-optic couplers with high coupling efficiency in thin-film AlN for both telecom (1550 nm band) and near-visible (780 nm band) light, and for both transverse magnetic (TM)-like and transverse electric (TE)-like modes simultaneously. Specific constraints due to the material properties of AlN and the extreme dimensions of adiabatic couplers required for high transmission efficiency make this task an outstanding challenge, especially for the 780 nm wavelength light. In order to exploit the largest $\chi^{(2)}$ component of c-plane AlN films, typical for those grown by physical-vapor-deposition or sputtering processes, TM-like modes of integrated photonic circuits should be used. On the other hand, high-efficiency adiabatic couplers require the tip size of the tapered waveguide to be sufficiently small (especially for the TM-like mode in thick films) to avoid insertion loss when interfacing with low-index optical fibers. However, in practice, the lateral dimension of fabricated AlN waveguides is limited by the tapering-out effect due to the dry etching process with best sidewall angles around 80° achieved so far [19]. Following these, it is thus a substantial challenge of realizing low-loss adiabatic couplers in thick AlN films by fabricating ultra-narrow waveguides with high aspect ratio.

To overcome this challenge, while balancing the strong optical nonlinearity and low-loss optical transduction that can be simultaneously achieved in AlN films, we developed a stepwise coupler for the 780 nm wavelength light, which shows an efficiency over 55% for both TM and TE polarizations in 600 nm thick AlN films. While for the 1550 nm wavelength light, using a flat-top coupler, the coupling efficiency is over 80% and 70% for the TM and TE polarization, respectively. Since for quantum photonic applications exploiting parametric down conver-
sion, including generation of squeezed light and entangled photons, 780 nm light merely acts as the classical pump while 1550 nm light contains the useful non-classical correlations, the realized fiber-optic couplers here ensure strong parametric photon interaction in the integrated photonic circuits while minimize the loss of quantum resources. A schematic of the stepwise coupler in AlN-on-insulator microchips is shown in Fig. 1a. The thickness of the AlN film is $H$. The released AlN waveguide coupler, anchored at an unreleased rib waveguide, has a thickness of $h$ and is adiabatically tapered from a width of $w_1$ to $w_2$ over a length of $L$. A tapered optical fiber is aligned side to the released waveguide over the tapering region to form the adiabatic fiber-optic coupler. As the simulation shows, for the 780 nm light, the released waveguide with reduced thickness (i.e. $h < H$) significantly increases the efficiency of the adiabatic coupler which is counteracted by the loss due to the waveguide-top step, but nevertheless the overall transmission efficiency is maximized with some optimal $h$. In contrast, for the telecom wavelength light, the released waveguide with full height (i.e. $h = H$) is able to achieve near-unity efficiency as the effective index of 1550 nm modes at the waveguide tip with practical dimensions is still sufficiently smaller than that of the optical fiber mode.

In the simulation of coupler efficiency, we assumed $H = 600$ nm and that the rib waveguide is 500 nm tall above the 100 nm thick AlN membrane. The cross-section of the AlN waveguide is assumed to be a trapezoid with the base angle of 80°, which resembles the fabricated AlN waveguide via dry etching process. The width of the waveguide coupler referred above, i.e. $w_1$ and $w_2$, is thus the width of the top surface of the waveguide. We fixed $w_1 = 50$ nm, $L = 24$ μm, and the aperture of tapered fibers to be 3.8°, for both near-visible and telecom light. For the 780 nm TM coupler, we varied $h$ and for each $h$ swept $w_2$ to maximize the overall coupling efficiency $\eta_t$ from the optical fiber to the unreleased rib waveguide, i.e. $\eta_t = \eta_c \eta_w \eta_s$, where $\eta_c$, $\eta_w$, $\eta_s$ are the efficiency of the adiabatic fiber-waveguide coupler, the stepwise waveguide junction, and the substrate etch-front, respectively. Fig. 2a shows the optimized $\eta_t$ for light of TM polarization and $\lambda = 773$ nm, while Fig. 2b shows the coupling efficiency for light of TE polarization in the same structure that optimizes the transmission of TM-like modes. We find $h = 300$ nm is appropriate in order to have high efficiency for both TM and TE polarizations, with $\eta_t = 69\%$ ($\eta_c = 97\%$, $\eta_w = 75\%$, $\eta_s = 95\%$ respectively) for the TM polarization achieved at $w_2 = 150$ nm. We note the efficiency for the TE polarization can potentially be higher as it is not yet optimized. Fig. 2a, shows the fundamental TM-like mode of the coupled fiber-waveguide system at a few locations for the optimized case. For the near-infrared light, using $h = 600$ nm, i.e. the full thickness of the AlN film, we optimized the coupling efficiency for light of TM polarization and $\lambda = 1546$ nm to be 91% at $w_2 = 350$ nm, and meanwhile the efficiency of the TE polarization is also 91% for the same structure.

We fabricated the designed couplers in AlN-on-insulator microchips with 600 nm thick AlN films deposited via a sputtering process with dual cathode S-gun magnetron source. The process is tuned such that the AlN thin-film is built in with 400 MPa tensile stress. Due to this tensile stress, the released waveguide couplers bend up out of the chip surface, enabling alignment with the tapered optical fibers. The integrated AlN photonic circuits with released adiabatic couplers are fabri-
cated using the following process. First, a window enclosing the to-be-fabricated 780 nm coupler is patterned with the AlN film thereof etched down by 300 nm in Cl$_2$/BCl$_3$/Ar-based inductively-coupled plasma-reactive ion etch (ICP-RIE). Then the photonic circuits including the couplers are patterned using electron beam lithography with HSQ mask followed by ICP-RIE to etch 500 nm AlN. Finally, a window enclosing the 1550 nm coupler, which is still protected by the residual HSQ from the previous beam write, is patterned and etched down by about 100 nm. The couplers are then released using hydrofluoric acid (HF) etch through the patterned windows while the rest photonic circuit is attached to the 100 nm thick AlN layer on the oxide substrate. The released couplers have a tilted angle $\sim 3^\circ - 5^\circ$. The tapered fibers are fabricated using HF etch [20, 21], by controlling the speed of the fiber pulling out of the HF liquid. For optimal coupling with on-chip waveguides, the fabricated fiber has an aperture $\sim 4^\circ$.

To test the efficiency of fabricated couplers, we used a photonic circuit consisting of two couplers connected by a short section of rib waveguide $\sim 40 \mu$m long. Two tapered fibers are used to measure the light transmission through the photonic circuit. Thus the average efficiency of the two couplers is characterized by $\eta_t = \sqrt{T}$, where $T$ is the fiber-to-fiber transmission efficiency. Fig. 3 shows the measured $\eta_t$ for light of TM and TE polarizations in the 780 nm and 1550 nm wavelength bands. The coupling efficiency for the 780 nm wavelength light is higher than 55% for both polarizations, and for the 1550 nm wavelength light it is over 80% for the TM polarization and over 70% for the TE polarization, respectively. However, the measured coupling efficiency is less than the simulation result, which could due to, for example, fiber misalignment and waveguide surface roughness (especially for the 780 nm coupler whose top surface is also etched in ICP-RIE), not to mention the measured efficiency is the average of two couplers.

To test the efficiency of fabricated couplers, we used a photonic circuit consisting of two couplers connected by a short section of rib waveguide $\sim 40 \mu$m long. Two tapered fibers are used to measure the light transmission through the photonic circuit. Thus the average efficiency of the two couplers is characterized by $\eta_t = \sqrt{T}$, where $T$ is the fiber-to-fiber transmission efficiency. Fig. 3 shows the measured $\eta_t$ for light of TM and TE polarizations in the 780 nm and 1550 nm wavelength bands. The coupling efficiency for the 780 nm wavelength light is higher than 55% for both polarizations, and for the 1550 nm wavelength light it is over 80% for the TM polarization and over 70% for the TE polarization, respectively. However, the measured coupling efficiency is less than the simulation result, which could due to, for example, fiber misalignment and waveguide surface roughness (especially for the 780 nm coupler whose top surface is also etched in ICP-RIE), not to mention the measured efficiency is the average of two couplers.

The demonstrated low-loss fiber-optic couplers are ready to interface with various integrated photonic circuits for exploiting nonlinear optical effects. As an example, we designed and fabricated a photonic circuit with a ring resonator coupled with both 780 nm and 1550 nm adiabatic couplers. (b) and (c) Reflection signal showing the 1550 nm TM resonances and 780 nm TM$_{20}$ resonances of the ring resonator, respectively.

The demonstrated low-loss fiber-optic couplers are ready to interface with various integrated photonic circuits for exploiting nonlinear optical effects. As an example, we designed and fabricated a photonic circuit with a ring resonator coupled with both 780 nm and 1550 nm wavelength bus waveguides. Such devices can be
used for efficient generation of entangled photon pairs and squeezed light on chips. A scanning electron microscopy image of the full device is shown in Fig. 1. The 780 nm bus waveguide, curled around the ring resonator to increase the coupling efficiency with the latter, is designed such that its TM\textsubscript{00} mode is phase-matched with the 780 nm TM\textsubscript{20} mode of the ring resonator. The ring resonator itself is designed so that its 780 nm TM\textsubscript{20} mode is phase-matched with the 1550 nm TM\textsubscript{00} mode for double-resonance enhanced nonlinear photon interaction. Both waveguides are terminated with photonic crystal mirrors for measurement of the resonator spectrum via reflected light using a single fiber for 780 nm and 1550 nm band individually. Fig. 4b and c show the measured 1550 nm band TM\textsubscript{00} and 780 nm band TM\textsubscript{20} resonances of the ring, with intrinsic quality factor of about $10^5$ and $0.8 \times 10^5$, respectively.

In summary, we have demonstrated a highly efficient fiber-to-chip interface in thin-film AlN using adiabatically tapered optical fibers and on-chip waveguides. This work will help establishing chip-scale entangled photon pairs and squeezed light sources in thin-film AlN with strong $\chi^{(2)}$ nonlinearity. The coupling efficiency of the fiber-optic couplers can be further improved by, for example, tuning ICP-RIE process to make narrower waveguides with smoother surfaces and adopting single crystalline AlN films [22].

Acknowledgements

This work is supported by US National Science Foundation under Grant No. DMS 18-39177. Authors thank Dr. Kaicheung Chow for assistance of device fabrication.

[1] Hong, C. & Mandel, L. Experimental realization of a localized one-photon state. *Physical Review Letters* **56**, 58 (1986).
[2] Slusher, R., Hollberg, L., Yurke, B., Mertz, J. & Valley, J. Observation of squeezed states generated by four-wave mixing in an optical cavity. *Physical Review Letters* **55**, 2409 (1985).
[3] Wu, L.-A., Kimble, H., Hall, J. & Wu, H. Generation of squeezed states by parametric down conversion. *Physical review letters* **57**, 2520 (1986).
[4] Silverstone, J. W., Bonneau, D., OBrien, J. L. & Thompson, M. G. Silicon quantum photonics. *IEEE Journal of Selected Topics in Quantum Electronics* **22**, 390–402 (2016).
[5] Xiong, C. et al. Compact and reconfigurable silicon nitride time-bin entanglement circuit. *Optica* **2**, 724–727 (2015).
[6] Dutt, A. et al. On-chip optical squeezing. *Physical Review Applied* **3**, 044005 (2015).
[7] Lu, X. et al. Chip-integrated visible–telecom entangled photon pair source for quantum communication. *Nature Physics* **15**, 373 (2019).
[8] Xiong, C. et al. Aluminum nitride as a new material for chip-scale optomechanics and nonlinear optics. *New Journal of Physics* **14**, 095014 (2012).
[9] Wang, C. et al. Monolithic lithium niobate photonic circuits for kerr frequency comb generation and modulation. *Nature communications* **10**, 978 (2019).
[10] Luo, R., He, Y., Liang, H., Li, M. & Lin, Q. Highly tunable efficient second-harmonic generation in a lithium niobate nanophotonic waveguide. *Optica* **5**, 1006–1011 (2018).
[11] Guo, X. et al. Parametric down-conversion photon-pair source on a nanophotonic chip. *Light: Science & Applications* **6**, e16249 (2017).
[12] Lenzini, F. et al. Integrated photonic platform for quantum information with continuous variables. *Science advances* **4**, eaat9331 (2018).
[13] Guo, X., Zou, C.-L., Jung, H. & Tang, H. X. On-chip strong coupling and efficient frequency conversion between telecom and visible optical modes. *Physical review letters* **117**, 123902 (2016).
[14] Wang, C. et al. Integrated lithium niobate electro-optic modulators operating at cmos-compatible voltages. *Nature* **562**, 101 (2018).
[15] Fan, L. et al. Superconducting cavity electro-optics: a platform for coherent photon conversion between superconducting and photonic circuits. *Science advances* **4**, eaar4994 (2018).
[16] Gröblacher, S., Hill, J. T., Safavi-Naeini, A. H., Chan, J. & Painter, O. Highly efficient coupling from an optical fiber to a nanoscale silicon optomechanical cavity. *Applied Physics Letters* **103**, 181104 (2013).
[17] Tielecke, T. et al. Efficient fiber-optical interface for nanophotonic devices. *Optica* **2**, 70–75 (2015).
[18] Burek, M. J. et al. Fiber-coupled diamond quantum nanophotonic interface. *Physical Review Applied* **8**, 024026 (2017).
[19] Sohn, D. B., Kim, S. & Bahl, G. Time-reversal symmetry breaking with acoustic pumping of nanophotonic circuits. *Nature Photonics* **12**, 91 (2018).
[20] Turner, D. R. Etch procedure for optical fibers (1984). US Patent 4,469,554.
[21] Hong, W., Liang, F., Schaak, D., Loncar, M. & Quan, Q. Nanoscale label-free bioprobes to detect intracellular proteins in single living cells. *Scientific reports* **4**, 6179 (2014).
[22] Sun, Y. et al. High-q resonators on single crystal aluminum nitride grown by molecular beam epitaxy. In *CLEO: Science and Innovations*, SF2I–6 (Optical Society of America, 2019).