EXPLOSIVE growth in the integration of a variety of sensors in mobile devices is currently underway and is rapidly dawning into the next revolution in hardware devices. The annually held IEEE SENSORS Conference and the IEEE SENSORS JOURNAL are now established as a premier meeting and technical publication in this area with worldwide participation by academic and industrial research institutions. The 12th IEEE SENSORS Conference was held at the Renaissance Harborsplace Hotel in Baltimore MD, USA on November 3–6, 2013. This special issue of the IEEE SENSORS JOURNAL includes 22 extended papers selected from the papers presented at this conference and represents the high-quality research presented at the conference.

The Technical Program was Chaired by Yogesh Gianchandani who led a technical committee consisting of 15 Track Chairs, experts in nine multidisciplinary topical areas, to conduct the overall program selection and peer review process. The nine Tracks and Chairs of the 2013 IEEE SENSORS Conference are:

Track 1—Phenomena, Modeling and Evaluation: Srinivas Tadigadapa, Penn State University, USA; Svetlana Tatic-Lucic, Lehigh University, USA.
Track 2—Chemical and Gas Sensors: Massood Atashbar, Western Michigan University, USA; Ponnambalam Ravi Selvaganapathy, McMaster University, Canada.
Track 3—Biosensors: Yu-Cheng Lin, National Cheng Kung University, Taiwan; Hongrui Jiang, University of Wisconsin, Madison, USA.
Track 4—Optical Sensors: Ignacio R. Matias, Universidad Publica de Navarra, Spain; Xiaojing (John) Zhang, The University of Texas at Austin, USA.
Track 5—Mechanical, Magnetic, and Physical Sensors: Kukjin Chun, Seoul National University, Korea; David Elata, Technion - Israel Institute of Technology, Israel.
Track 6—Sensor/Actuator Systems: Oliver Paul, IMTEK, University of Freiburg, Germany; Gijs Krijnen, MESA+ Research Institute for Nanotechnology, University of Twente, Enschede, Netherlands.
Track 7—Sensor Networks: Thomas Newe, University of Limerick, Ireland.
Track 8—Applications: David A. Horsley, UC Davis, USA
Track 9—Other Sensor Topics—Materials, Processes, Circuits, Signals & Interfaces: Kenichi Takahata, University of British Columbia, Canada.

A total of 951 abstracts were submitted from 41 countries spanning the major regions of the world. Of these 252 were presented in lecture sessions which included 16 invited presentations and 278 were presented as posters of which 22 were open posters. Based on the peer review scores from six reviewers (first review) of the submitted abstracts, the top 10 abstracts and conference publications were reviewed by the Track Chairs (second review) and the top two or three papers in each of the nine areas were invited to submit full manuscripts for this special issue of the Journal. Thus, the papers in this collection represent the top 4% of all the accepted papers presented at the IEEE SENSORS Conference, 2013.

The Guest Editors of this Special Issue thank all the Track Chairs for their effort in helping to select the best papers as well as all the reviewers who assisted in the critical and timely review of all the submitted papers. We are especially thankful to Alison Larkin at the IEEE for helping us stay organized and move through the process in a timely fashion. Finally, we would like to congratulate all the authors for their excellent work and their participation in this issue.

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An Optomechanical Transducer Platform for Evanescent Field Displacement Sensing

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Abstract— We demonstrate an integrated waveguide platform and optomechanical transduction circuit for chip-scale displacement sensing. The waveguide consists of a thin silicon nitride core layer, a thick silicon oxide bottom cladding, and a top air cladding with a large evanescent field at the waveguide surface. Although the structures feature subwavelength (\(<\lambda/4\)core) vertical confinement, they are fabrication tolerant with micrometer-scale lateral features. We demonstrate via simulations and measurements that the waveguides exhibit a low confinement with a maximized evanescent field as well as an effective index only slightly larger than the SiO2 bottom cladding index. Despite the low confinement, the waveguide platform enables complex photonic circuits. As a demonstration of this technology, we fabricate and characterize an unbalanced Mach–Zehnder interferometer for chip-scale displacement sensing. A micrometer-scale fiber taper interacts with the waveguide’s evanescent field and induces a phase shift proportional to displacement, thereby acting as an optomechanical transducer. We analyze the responsivity, displacement limit of detection, and strength of optomechanical coupling for high-resolution sensing. An outlook toward other applications is also given.

Index Terms—Interferometers, mechanical sensors, microelectromechanical systems, micromachining, optical waveguides, optoelectronic and photonic sensors.

I. INTRODUCTION

INTEGRA TED optical sensors take advantage of the high sensitivity and relative noise immunity of optical devices. In particular, waveguide-based structures enable the large-scale integration of many sensors on a single chip platform using low-cost batch fabrication processes. In general, optical waveguide-based sensors rely on the effect of liquids or gases on the propagation of light in a waveguide [1], e.g. by changing the absorption or effective index. We recently developed a sensor with highly-evanescent light propagation in functionalized microring resonator cavities [2] in which trace chemical vapors are measured via the wavelength-dependent change in absorption (absorption spectroscopy).

Besides chip-scale absorption sensing, there is also a need for measuring small displacements. Such transducers are required for pressure sensors, accelerometers, bolometers and micromechanical photothermal spectroscopy [3]. In particular, photothermal-based sensors [3] enable the spectroscopic detection of chemical analytes by transducing a change in absorption into a displacement that can be measured. Regardless of the particular application, integrated optical approaches offer several benefits including compactness, passive operation, and relative immunity to electromagnetic interference. Optical waveguide-based interferometric approaches are highly sensitive and enable large-scale integration compared to e.g. surface-normal Fabry-Perot cavities [3], which cannot be easily interconnected on-chip.

Optical sensors that rely on the evanescent field perturbation of a propagating mode are well-established [4]–[9]. In most integrated waveguides and optical fibers the optical mode is tightly confined and the evanescent field is small. However, in optical sensors that rely on the interaction of a measurand with the optical mode it is necessary to have a significant evanescent field since this field is the essential transducer; i.e. it is desirable to have a considerable fraction of the optical field outside of the waveguide (or fiber) core. In fact, for homogenous sensing in which a change in the cladding index is to be measured it has been shown theoretically that the maximum sensitivity for TE-polarization is obtained in thin core waveguides that operate close to mode cut-off [4] since this ensures a weak mode confinement and a large evanescent field. However, few sensor demonstrations have focused on optimizing the evanescent field. In general, most waveguide sensors have utilized core thicknesses in the range of \(\lambda/2n_{\text{core}}\) [5]–[9] without considering how the waveguide design affects the evanescent field profile and sensor performance. An alternate approach to improve sensitivity has been to increase the optical path length (i.e. effective waveguide length) through the use of optical cavities [10]–[14], and indeed extremely high sensitivity has been achieved in high-Q optomechanical cavities [15], [16]. In this work we optimize the device sensitivity by designing a simple optical waveguide that exhibits the lowest possible mode confinement to maximize the evanescent field. This optimized waveguide design can find application in a number of sensors [4]–[14] by enhancing the evanescent field interaction strength without the need for a high-Q optical cavity. Although we focus on chip-scale...
displacement sensing via optomechanical transduction, the design approach can also be applied to other devices ranging from chemical sensors to nanoparticle trapping to cold atom systems.

II. APPROACH: LOW MODE CONFINEMENT WAVEGUIDE

The basic silicon nitride waveguide architecture shown in Fig. 1 exhibits a large evanescent field. Before discussing our approach in detail, it is useful to place this work into context. Silicon nitride waveguides have been extensively demonstrated [17]–[21], although the core thickness has generally been of the order of \( \lambda/2n_{\text{Core}} \), which results in relatively tight confinement with a low evanescent field and low-loss. More recently, waveguides with deeply sub-wavelength Si₃N₄ core thickness (~50 nm) have been demonstrated with ultra-low loss [22]. However, these waveguides require a very thick top and bottom SiO₂ cladding (>10,000 nm) which prevents access to the evanescent field. Other demonstrations of thin-core, highly evanescent waveguides have been in suspended III-V semiconductors [23], [24], although the focus was on reducing propagation loss [23] or on bi-refrangent phase matching for difference frequency generation [24]. Suspended waveguides [23], [24] can result in exceptionally low mode confinement with access to the evanescent field at the waveguide top and bottom; however, they can be challenging to fabricate and reliability can be an issue. Optical waveguides coupled to opto-mechanical structures via evanescent field interaction have also been demonstrated [25]–[29], although they have generally utilized thick (or wide) waveguide cores >\( \lambda/2n_{\text{Core}} \) [25]–[28]. Our waveguide architecture shown in Fig. 1ab improves upon previous work by providing access to the largest possible evanescent field while enabling simple and low-cost fabrication in a robust architecture. While various optical readout circuits [6], [10]–[14], [30]–[33], including Mach-Zehnder interferometers [6], [30]–[33], have already been demonstrated they have not considered the evanescent field in detail and no systematic study was done to optimize this critical aspect of evanescent field sensors. Therefore, these prior demonstrations [4]–[14] can also benefit from an improved evanescent field waveguide design.

Our Si₃N₄/SiO₂ optical waveguide platform utilizes a silicon nitride core thickness of \( t_{\text{Si₃N₄}} \approx \lambda/4n_{\text{Core}} \). The 175 nm Si₃N₄ waveguide core is deposited via low-pressure chemical vapor deposition (LPCVD). The evanescent field can be optimized by simply modifying the Si₃N₄ core layer deposition thickness, which can be controlled precisely using common film deposition tools. The lower cladding is 3,000-5,000 nm (depending on the sample) of thermal silicon dioxide (SiO₂). We focus on an air top cladding since most sensors require interaction with the evanescent field at the waveguide surface.

We use a shallow rib with a depth of \( H_{\text{Rib}} = 55 \) nm with micron-scale lateral dimensions (\( W_{\text{Rib}} = 1.0-2.5 \mu \text{m} \)). The TE₂₀-mode at \( \lambda = 1550 \) nm (Fig. 1ab) shows that at the waveguide surface the evanescent field is 70 % of the peak Ex-field value inside the core; it drops down to 25 % at 100 nm above the waveguide surface. For most applications, the total fractional power contained above the waveguide surface is of interest, which we analyze in more detail in the next section. The large evanescent field makes these waveguides highly-sensitive to a perturbation near the surface, which changes the waveguide effective index (\( n_{\text{Effective}} \)). Any device that relies on evanescent field interaction can benefit from the low confinement waveguide in Fig. 1. Specifically, we focus on displacement sensing in which an opto-mechanical perturber interacts with the waveguide’s evanescent field (Fig. 1c). This interaction modifies the waveguide’s effective index so that a measurement of \( n_{\text{Effective}} \) enables us to extract a displacement.

The \( n_{\text{Effective}} \) can be measured in a number of ways, e.g. using optical cavities [10]–[14]. Optical cavities enable narrow resonance linewidths, which make them highly-sensitive to small changes in the waveguide propagation characteristics. However, the narrow linewidths can also limit their dynamic range and can make them temperature sensitive due to thermo-optic effects. An alternative interferometric readout circuit is a Mach-Zehnder interferometer (MZI) [6]. This readout approach, while not as sensitive as cavity-based approaches, is less temperature dependent due to its larger optical bandwidth compared to cavities and may therefore be preferred for field applications. In particular, Si₃N₄/SiO₂ waveguides have a thermo-optic coefficient roughly one order of magnitude smaller than silicon [34] making this approach highly-tolerant of temperature fluctuations. Furthermore, MZI’s can still provide exceptional sensitivity, and are more than sufficient for some applications, e.g. photothermal spectroscopy [3].

III. DESIGN AND SIMULATION

A. Waveguide Mode and Evanescent Field Simulations

A commercial software package [35] is used to optimize the waveguide design. For all simulations the lower SiO₂ cladding thickness is \( t_{\text{SiO₂}} = 5,000 \) nm. Only TE-polarization is considered since TM results in large substrate leakage. We first determine the optimal core thickness (\( t_{\text{Si₃N₄}} \)) for
The simulations in Fig. 2 show that there is little to be gained by moving towards thinner $t_{\text{Si3N4}}$ beyond the optimal thickness. Any further decrease in $t_{\text{Si3N4}}$ reduces the evanescent field above the waveguide surface since the mode is then pulled down towards the substrate and more closely resembles a strip loaded waveguide. However, the finite bottom cladding thickness ($t_{\text{SiO2}} = 5,000$ nm) means that as the mode is pulled down it also interacts with the underlying silicon resulting in substrate leakage loss. We find that the loss starts increasing roughly when the waveguide effective index approaches that of the SiO2 bottom cladding. Therefore, while we want $n_{\text{Effective}}$ to be small since this implies a weak mode confinement with a large evanescent field, we also require $n_{\text{SiO2}} < n_{\text{Effective}} < n_{\text{Core}}$. In fact, by considering the fractional evanescent field power as our figure of merit we find that the optimal core thickness results in $n_{\text{Effective}} \approx 1.5$ which is still considerably larger than $n_{\text{SiO2}} \approx 1.46$.

We can quantitatively identify the optical loss associated with substrate leakage, since the $n_{\text{Effective}}$ simulation includes an imaginary component where the loss is $\alpha(\text{imag.}) = 4\pi n_{\text{Effective}}(\text{imag.})/\lambda$. For $t_{\text{Si3N4}} = 175$ nm the simulated loss is in the range of $0.1$-$1.0$ dB/cm at $\lambda = 1550$ nm. These loss values are rough estimates (the imaginary component of $n_{\text{Effective}}$ is in the range of $10^{-4}$-$10^{-7}$) and do not include contributions from sidewall roughness. Nonetheless, they are useful design guidelines for maximizing the evanescent field while enabling practical devices with reasonable loss. In addition, the propagation loss needs to be considered to determine the maximum sensing length over which evanescent field interaction can occur. Finally, although not considered in detail here, the mode simulations in Figs. 1-2 also enable the design of the waveguide mode profile to ensure mode-matching for low-loss fiber-chip coupling and packaging.

### B. Optical Readout Circuit

The readout circuit is based on an asymmetric (or unbalanced) MZI that enables measurement of $n_{\text{Group}}$ and $n_{\text{Effective}}$. In contrast to deeply-etched waveguides that enable small radius with low-loss [21], bend loss is a significant consideration in our low mode confinement waveguides. By performing a mode simulation of a curved waveguide, the imaginary $n_{\text{Effective}}$ and expected bend loss can be obtained. For a typical $100$ $\mu$m long curved waveguide segment the expected bend loss is $\alpha_{\text{Bend}} = 0.05$-$0.5$ dB for $W_{\text{Rib}} = 2.5$-$1.5$ $\mu$m and radius $R = 500$ $\mu$m. Although this results in a larger footprint compared to deeply-etched waveguides, compact devices can still be realized.

Our MZI circuit utilizes directional couplers as power splitters/combiners at the input/output. The coupling efficiency is related to the difference in propagation constants between the even and odd modes of the coupled waveguide system [36]. Due to the weak mode confinement, strong coupling is possible between adjacent waveguides resulting in compact directional couplers. Figure 3 shows beam propagation method (BPM) [35] simulation results for various configurations assuming $t_{\text{Si3N4}} = 175$ nm, $H_{\text{Rib}} = 55$ nm, TE-polarization, and $\lambda = 1550$ nm. Compact 3 dB splitters/combiners can be realized with lengths $L_{3\text{dB}} < 100$ $\mu$m.
The response of an asymmetric MZI with built-in path length imbalance \( L_0 \) is given by \( I(\phi) = I_1 + I_2 + 2(I_1 I_2)^{1/2} \cos(\phi) \) \[36\], where \( I_1 \) and \( I_2 \) are the intensities in the signal (i.e. measurand) and reference waveguide arm, respectively, \( \phi = 2 \pi \Delta L/\lambda \) is the phase, and \( \Delta L = (n_{\text{Effective}} + \Delta n_{\text{Effective}}) L_0 \) is the optical path length difference between the signal and reference arms that includes both built-in \( (n_{\text{Effective}} L_0) \) and measurand-induced changes \( (\Delta n_{\text{Effective}} L_0) \) in optical path length. The two outputs of an MZI (BAR and CROSS) are 90 degrees out-of-phase. For perfectly balanced intensities \( I = I_1 = I_2 \) the MZI can exhibit large extinction provided that there are no sources of noise, e.g. from light scattering or reflection from facets. To reduce facet reflections, we incorporate angled facets at the input and output of the chip to help reduce noise and increase extinction. An asymmetric MZI shows a periodic response with wavelength that is determined by the waveguide’s \( n_{\text{Effective}} \). The wavelength spacing between maxima (minima) of the MZI spectrum is a function of the group index, i.e. the free-spectral range \( FSR = \frac{\lambda^2}{n_{\text{Group}} L_0} \). In this work we consider two MZI designs with \( L_0 = 86 \mu m \) and 100 \( \mu m \) resulting in an \( FSR \approx 14 \) nm and \( FSR \approx 16 \) nm, respectively.

C. Waveguide Fabrication

We start with commercially available 325 \( \mu m \) thick Si(100)/SiO2/Si3N4 wafers with 175 nm thick Si3N4 core layer \( n_{\text{SiN4}} \approx 2.0 \) deposited via low-pressure chemical vapor deposition (LPCVD) on a 3,000 nm – 5,000 nm thick layer (depending on fabrication run) of thermal SiO2. The waveguides are patterned either via e-beam or contact lithography. Although the feature sizes are large (1 \( \mu m \) and greater) allowing for simple contact lithography to be used, e-beam lithography results in lower waveguide propagation loss likely due to smoother sidewalls. Next, the pattern is transferred into the Si3N4 core layer using an SF6/CF8 ICP/RIE dry etch. The shallow 55 nm rib etch can be achieved to within a few percent owing to the slow etch rate, generally 15-20 nm/min, and by performing a calibration etch. Next, a laser is used to scribe cleave marks along the edge of the wafer to define chips as small as 2.4 mm. The chips are then cleaved to obtain smooth and reproducible waveguide facets.

IV. EXPERIMENTAL RESULTS

A. Waveguide Characterization

We characterize our devices using a tunable laser (\( \lambda = 1440-1640 \) nm, TE-polarization), lensed polarization-maintaining fibers for coupling to and from the chip, and a photodetector. Our waveguides are single-mode for \( \lambda > 1500 \) nm, although the widest waveguide \( (W_{\text{Rib}} = 2.5 \mu m) \) supports a higher-order mode for \( \lambda < 1500 \) nm. A typical transmittance spectrum for a \( W_{\text{Rib}} = 2.0 \mu m \) waveguide is shown in the inset of Fig. 4a; Fabry-Perot fringes arise from reflections from the cleaved waveguide end-facets. The propagation loss is extracted from relative transmission measurements performed on samples of different lengths obtained via cut-back \( (L = 2.4 \) mm, 4.8 mm, 7.2 mm, and 9.6 mm). At \( \lambda = 1440 \) nm the loss is \( \alpha = 0.7 \) dB/cm. Near \( \lambda = 1520 \) nm there is a well-known absorption peak due to Si-H bonds in the Si3N4 [18], which can be avoided in future devices by annealing [18], [20]–[22]. At long wavelengths (\( \lambda > 1590 \) nm) the mode becomes very weakly-confined and the loss increases significantly. The loss spectrum for \( W_{\text{Rib}} = 2.5 \mu m \) is similar. However, for \( W_{\text{Rib}} = 1.0–1.5 \mu m \) the propagation loss is substantially larger (\( \alpha = 4-7 \) dB/cm at \( \lambda = 1440 \) nm), likely due to increased scattering loss as well as weaker mode confinement which increases the substrate leakage loss. The simulated loss is in good agreement with measurements in terms of reproducing substrate leakage loss from the imaginary \( n_{\text{Effective}} \), although the simulations do not consider other sources of loss (e.g. scattering from sidewall roughness).
The propagation loss and facet reflectivity can also be extracted from the Fabry-Perot spectrum in Fig. 4a by analyzing the fringe contrast [37]. The propagation loss is in agreement with the relative transmission measurements. More importantly, the extracted facet reflectivity is in the range of $R = 5-6\%$, significantly less than the Fresnel reflectivity of silicon nitride, $R_{\text{Si3N4}} = [(n_{\text{Si3N4}} - 1)/(n_{\text{Si3N4}} + 1)]^2 \approx 11\%$. This indicates that the waveguide mode propagates substantially outside of the Si3N4 core. An approximate value of the facet reflectivity can be found using the waveguide effective index to obtain $R_{\text{Eff, Index}} \approx 4\%$ in agreement with our measurement. The low reflectivity is an indication of the waveguide’s low confinement and large evanescent field and provides evidence that our modeling accurately describes the fabricated devices.

The Fabry-Perot spectrum also enables us to extract the waveguide group index, since the fringe spacing is related to the group index by $FSR = \lambda^2/(n_{\text{Group}}L_{\text{Waveguide}})$. The measured $n_{\text{Group}}$ is shown in Fig. 4b and is in excellent agreement with the simulated values for $W_{\text{Rib}} = 1.0-2.5 \mu m$. The measurements therefore provide further evidence that our modeling (Fig. 2) enables the design of waveguides with a large evanescent field and an optimized fractional power in the air region.

**B. Optical Readout Circuit Characterization**

Next, we characterized the asymmetric MZI optical readout circuit (Fig. 5a-c). Figure 5d shows measured spectra for an MZI with $W_{\text{Rib}} = 2.0 \mu m$, directional coupler length $L_{\text{Coupler}} = 50 \mu m$ and coupler gap $g_{\text{Coupler}} = 1.0 \mu m$. The MZI shows balanced splitting between the two arms, in agreement with the directional coupler simulations, and a complementary response between the BAR and CROSS outputs, as expected. We extract an $n_{\text{Effective}} \approx 1.49$ by fitting the measured MZI fringe spectrum to the theoretical response and find good agreement with effective index simulations. The MZI insertion loss is around 1.3 dB (at $\lambda = 1444nm$) compared to a test waveguide on-chip. We attribute the insertion loss to the multiple waveguide bends in the directional couplers and MZI. The spectra in Fig. 5d show significant reflections arising from the flat input waveguide facet, although they are substantially less than the Fabry-Perot fringes in Fig. 4a, which resulted from flat input and output facets. Figure 5e shows a measured spectrum for an MZI that had angled input and output facets. The extinction in this device is as large as 30 dB, which we attribute to the reduction of facet reflections, which can scatter light and thereby reduce extinction. By properly packaging the devices with optimized fiber pigtails we expect to minimize scattered light in the chip. The measurements in Fig. 5d, e illustrate two important considerations for an optical readout circuit: 1) proper balancing of power between the two arms (even splitting in the directional coupler) to ensure large extinction, and 2) reducing scattering to decrease noise. Both issues are critical for measuring small phase shifts induced by perturbations, e.g. by the displacement of an optomechanical structure near the waveguide surface (Fig. 1c).

**C. Displacement Sensing via Optomechanical Transduction**

As a demonstration of displacement sensing we use a tapered optical fiber as an off-chip optomechanical perturber; future sensors will utilize an on-chip integrated perturber (Fig. 1c). A standard SMF-28 optical fiber was tapered using a commercial splicing system in which a plasma discharge produced a localized heating of the fiber while the tension at the fiber ends was precisely controlled. In this manner, fiber tapers with diameters of 8 $\mu m$ were fabricated. The fiber taper was mounted onto a voltage-controlled XYZ-micro-positioner and displaced just above the BAR waveguide (Fig. 6a). The tapered fiber interacts with the waveguide evanescent field and induces a phase shift. The perturber’s index ($n \approx 1.47$) effectively increases the waveguide top cladding index ($n_{\text{Air}}$) resulting in a change in the waveguide $n_{\text{Effective}}$. The phase shift can be measured by observing the fringe shift as the fiber-perturber is displaced (Fig. 6a, inset). Alternatively, the laser wavelength can be fixed while the MZI transmittance is continuously monitored to obtain displacement information in real-time (Fig. 6b). We set the laser wavelength to a region where $dI/d\lambda$ is maximized ($\lambda = 1471.1$ nm), i.e. at a quadrature point where the CROSS output drops to...
approximately 50%. An automated LabVIEW program was used to control the micro-actuators such that the fiber perturber was displaced towards the MZI waveguide surface in increments of $Δz = -20$nm (set by the displacement resolution of the actuators). The CROSS response is non-linear with displacement, as expected, since the evanescent field decays exponentially away from the waveguide core (measurements using the BAR output showed a similar response). The measurements in Fig. 6b indicate nanometer-level displacement sensitivity using this simple off-chip perturber setup.

We can estimate the displacement measurement noise as follows. First, the displacement responsivity is found from the linear slope $R = \frac{dCROSS(V)}{dz(nm)} = 0.75$ mV/nm measured over the displacement range $z = 0$-40nm in Fig. 6b. The signal noise ($V_{\text{noise}}$) is obtained from the measured SNR in an MZI without a fiber perturber, resulting in $SNR = 25$-30dB. The displacement noise is then found from $z_{\text{noise}} = V_{\text{noise}}/SNR$. Noting that the displacement measurements in Fig. 6b were taken with an integration time $τ = 16.67$ms (measurement bandwidth $BW = 1/2πτ = 9.5$Hz) results in a displacement noise of $z_{\text{noise}} = 123$ pm/Hz$^{1/2}$ (388 pm/Hz$^{1/2}$) for an $SNR = 30$dB (25dB); the corresponding displacement limit of detection at 9.5Hz measurement bandwidth is $LOD_{Δz} = 40$ pm ($SNR = 30$dB) and $LOD_{Δz} = 126$ pm ($SNR = 25$dB).

Although repeated measurements showed a similar response and displacement sensitivity, the fiber was actuated until it made contact with the waveguide surface, which resulted in a small lateral shift in the fiber position after it was lifted. Given the small waveguide dimension ($W_{\text{Rh}} < 2.5$ μm) compared to the minimum fiber diameter (8 μm), small lateral shifts of the fiber perturber resulted in large changes in perturber-waveguide interaction conditions. We expect that future sensors, in which the tapered fiber is replaced with an on-chip and integrated optomechanical perturber, will enable precise control of the waveguide-perturber interaction with reproducible conditions. An integrated perturber also enables higher responsivity since the interaction length ($L_{\text{Interaction}}$) between the perturber and waveguide can be increased resulting in a larger phase shift $Δϕ ∼ Δn_{\text{Effective}}L_{\text{Interaction}}$.

In our measurements the bandwidth is set by the integration time of the digital multi-meter, or $τ = 16.67$ms (BW = 9.5 Hz), although this bandwidth is arbitrary. For some applications, e.g. photothermal spectroscopy for chemical sensing [3], we are interested in steady-state displacements and the integration time can be increased (BW decreased) since the sensor temporal response is dominated by other factors, such as analyte diffusion time. Reducing the measurement bandwidth should result in an enhanced displacement sensitivity since e.g. shot noise is proportional to $\sqrt{BW}$ [32].

V. DISCUSSION

A. Noise Sources

The performance of any sensor is dependent on noise and signal-to-noise ratio (SNR). A detailed survey of noise sources in fiber-optic sensors is given in [38], and many of the same issues are applicable here. Briefly, some noise sources include laser noise, detector noise, readout circuit noise, polarization fading [39] and thermal-mechanical vibration noise [40] of the perturber. Laser noise includes both intensity and phase noise, and high-quality optical sources are critical to obtain low noise. The low absorption and small thermo-optic coefficient of Si₃N₄ and SiO₂ enable the operation at high optical powers, thereby minimizing the effects of shot noise. Our optical readout circuit noise is dominated primarily by scattered light resulting from a mode mismatch between the tapered lensed input fiber and our thin Si₃N₄ core waveguide (sidewall roughness can also increase scattering). Measurements on a simple test waveguide on-chip have shown that at optimal coupling conditions the SNR $\sim 25$ dB and that this is reduced when coupling is not optimized. Therefore, packaging and fiber-coupling is an important consideration not just for power efficiency but also to ensure low noise by preventing on-chip light scattering. Finally, thermal-mechanical vibration [40] of the mechanical perturber can be a desired measurand if the mechanical resonance of the perturber is to be measured. On the other hand, thermal-mechanical vibration results in a noise signal for DC displacement measurements, as in [3]. If the application permits, operation at small BW (long integration times) will minimize this noise term.

B. Displacement Sensitivity and Optomechanical Coupling

Our measurements have demonstrated nanometer-level displacements, although the true interaction length between the fiber-perturber and waveguide is difficult to ascertain. Therefore, we consider a fully-integrated sensor as shown schematically in Fig. 7a to estimate the displacement limit.
of detection. We consider a 200nm thick Si3N4 micromesh bridge that is suspended above the waveguide surface via an SiO2 sacrificial layer. We choose a perturber thickness \(t_{Si3N4} = 200\text{ nm}\) since this gives a perturber \(n_{\text{Effective}} \approx 1.340\) (\(\lambda = 1550\text{ nm}\), TE), which is considerably smaller than the waveguide \(n_{\text{Effective}} \approx 1.478\) and therefore prevents significant power coupling between the two structures. The simulated displacement responsivity is shown in Fig. 7b and shows a strong increase in \(n_{\text{Effective}}\) as the micromesh-waveguide gap \((\Delta z)\) is decreased. Such large changes in \(n_{\text{Effective}}\) are not readily achievable by other means (e.g. via thermo-optic or electro-optic effects) and suggest that evanescent field interaction is also useful for optomechanical phase shifters. For sensing applications, the transducer responsivity is \(dn_{\text{Effective}}/d\text{gap}\) and approaches \(10^{-3}/\text{nm}\) for \(\text{gap} = 50\ \text{nm}\) (blue curve). A common metric for comparing transduction between optical and mechanical structures is the coupling coefficient \(g_{OM} = \frac{d\omega}{dz} = (1/n_{\text{Effective}})(dn_{\text{Effective}}/dz)(\epsilon/\lambda)\) [28], [41]. Due to the large evanescent field, we achieve strong optomechanical transduction with \(g_{OM} > 10\ \text{GHz/nm}\). In contrast, such large \(g_{OM}\) has been demonstrated in cavities [14], [15], [41], [45], while devices without cavities typically give \(g_{OM} \approx \text{GHz/nm}\) [28], [41]. Concerning ultimate displacement resolution, the present device is well-suited for applications such as photothermal spectroscopy [3] and the architecture in Fig. 7a is simpler than cavity-based devices, although it is less sensitive than ultra-high-Q cavity optomechanical systems [15], [16], [44]–[46].

While the measurement bandwidth is important for any sensing application, a more general analysis of displacement sensitivity considers SNR (dB) as opposed to noise per unit bandwidth \((\text{noise}/\sqrt{\text{Hz}})\). Starting with the output intensity of an MZI, the displacement responsivity for a displacement \(z\) is \(dI/dz = I_0 (4\pi \Delta z/\lambda) \sin (2\pi L_0 n_{Eff}/\lambda)(dn_{Eff}/dz)\), where the MZI path length imbalance is set as \(L_0 = 250\ \mu\text{m}\) and the phase shift is assumed to occur over this same interaction length \(L_0\). The minimum displacement that can be measured is found by setting \(I_{\text{Noise}} = \Delta z \text{Min}(dI/dz)\) and solving for displacement, which gives \(\Delta z \text{Min} = I_0 \exp(\text{SNR}/10)/(dI/dz)\). We find that for an \(\text{SNR} = 25\text{-}30\text{dB}\), as measured in our MZI, the displacement limit of detection is \(\text{LOD}_{\Delta z} = 10\text{-}100\ \text{picometers}\). Indeed, the measured displacement noise (data points in Fig. 7c) obtained from the measured device responsivity \(R\) (Fig. 6b) shows good agreement with the calculated values. Improvements in the readout circuit’s SNR (e.g. by minimizing scattering resulting from mode-mismatch between the input lensed fiber and the on-chip waveguide) will improve this \(\text{LOD}_{\Delta z}\). Enhanced measurement techniques, e.g. by using phase sensitive lock-in detection, can further enhance the SNR so that picometer-level displacement sensitivity should be possible. The measurement of mechanical resonances of the microbridge perturber should give a similar enhancement since broadband noise can be rejected in favor of a narrowband mechanical signal.

Finally, the MZI readout approach offers significantly higher displacement resolution compared to similar chip-scale capacitive-based sensors. Such devices typically have a displacement resolution in the nanometer to micrometer range [42], [43]. Compared to capacitive readout methods, which require on-chip electrical power, optical techniques offer the prospect of remotely-interrogated passive sensors.

C. Optical Forces

Strong optomechanical coupling (i.e. large \(dn_{\text{Effective}}/dz\) or \(dn_{\text{Effective}}/d\text{gap}\)) not only implies a large change in optical propagation with mechanical displacement but also implies an optical force that acts on the mechanical perturber. This gradient optical force is proportional to \(dn_{\text{Effective}}/d\text{gap}\) [29] as well as the interaction length and the optical power. In our experiments we did not observe any significant effect of optical forces at the laser power used (500\ \mu\text{W}). Calculations for a typical \(dn_{\text{Effective}}/d\text{gap}\) in the sensor show that the induced optical forces are in the 10-100 pico-Newton range (dependent on interaction length and optical power), generally too small to induce significant displacement on the perturber. Compared to an MZI, optical radiation pressure forces [40] are much stronger in cavity-based readout circuits due to the optical power enhancement when operating at resonance, which leads to a proportional increase in the optical force. Furthermore, optical cavities exhibit backaction [44]–[46], which leads to feedback between the optical and mechanical structures that complicates the mechanical dynamics.
While strong optical forces in cavity optomechanical systems are an exciting area of research, they can be detrimental to an optomechanical displacement sensor and should be considered. In addition to feedback, optical cavities also have a limited dynamic range due to their narrow optical linewidth. The absence of feedback and the larger optical bandwidth in an MZI simplifies the dynamics and is a significant advantage of this readout approach. The large evanescent field enables operation far from the waveguide surface, where the responsivity is smaller, but the reduced $\text{d}n/\text{d}g$ also leads to a smaller optical force. Finally, for large SNR it is possible to operate at lower optical powers and smaller $F_{\text{optical}}$.

VI. CONCLUSION

We presented a low confinement waveguide platform that enables a large evanescent field. An unbalanced MZI was demonstrated as a readout circuit for chip-scale displacement sensing using optomechanical transduction via displacement-induced changes in the waveguide effective index. The large transparency window of Si$_3$N$_4$/SiO$_2$ makes this waveguide technology applicable to many other areas, and the techniques presented here can be adapted to optimize the evanescent field at a variety of wavelengths of interest for chemical sensing [2], [3], nanoparticle trapping [9], and cold atom systems [47].

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