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InP-based grating antennas for high resolution optical beam steering

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Abstract—Optical beam steerers on InP integrated photonics have not been able to offer high angular resolution, due to the technological challenges in realizing a large emission aperture. In this paper, we propose the creation of waveguide-based grating antennas fabricated in SiO2 super-cladding on InP membrane on silicon (IMOS) to achieve simultaneously high resolution and good compatibility with InP-based active devices. By exploiting the high dry etch selectivity between SiO2 and InP, a tolerant fabrication process is proposed and demonstrated, allowing for high controllability in the process. Device parameters including buffer thickness and pitch have been explored to obtain an optimized design. A 2-mm long grating antenna is fabricated and shows a record narrow full-width-half-maximum angular beam width of 0.05° and a high spatial resolution of more than 250 points when the wavelength is tuned over a range of 100 nm.

Index Terms—LiDAR, beam steering, InP photonics, optical phased array, waveguide grating.

I. INTRODUCTION

HIGH resolution optical beam steering is a key enabling technology for light-based detection and ranging (LiDAR), secure free-space optical communication and holographic displays. The market for fast, precision LiDAR is expected to grow into multi-billion euro scale in the near future [1], due to its potential mass adoption in drones and self-driving cars. However, real-world scenarios raise several challenges to current optical beam steering technology, including cost, durability, resolution, speed and power handling. Specifically, to detect small objects like pedestrians at a distance of 200 m in real-time, a beam divergence of less than 0.1° and a framerate of more than 10 Hz are required [2].

To address the growing demand for high performance beam steerers, many schemes based on different technologies have been proposed, including mechanical scanning [3], micro-electro-mechanical systems (MEMS) based steering [4], vertical-cavity surface-emitting laser (VCSEL) arrays [5], and on-chip optical phased arrays (OPA) [6]. Empowered by the photonic integration technology, on-chip OPAs have a great potential of becoming the mainstream technology in the long term, due to its high reliability, high scalability, mass-manufacturability and route to low cost.

Various types of 2-D scanning on-chip OPAs have been demonstrated, using either matrices of separate antennas where each antenna needs to be individually phase-controlled [7,8], or on-chip grating antenna (GA) arrays in which wavelength tuning and direct phase modulation steer the beam in two directions separately [9-13]. Sub-0.1° full width half maximum (FWHM) beam divergence has been demonstrated using the GA approach on both silicon-on-insulator (SOI) and silicon nitride [14] platforms, but not yet on InP-based platforms.

On SOI, it has been challenging to realize high efficiency, high density phase modulator (PM) arrays and semiconductor optical amplifier (SOA) arrays, which are however essential to a low power consumption, high speed, high output power beam steerer. Currently, SOAs or PMs on SOI are realized by either III-V chip/die attachment (e.g., flip-chip bonding, die-to-wafer bonding and transfer printing) or heteroepitaxy [15,16]. These “III-V on Si” approaches face challenges in nanometer-scale alignment, limited throughput, large tapers for optical coupling and thick buffer layers, respectively.

In contrast, InP [17], a platform with a comprehensive set of optical functionalities including lasers, SOAs, PMs and photodetectors, provides all the building blocks for constructing a high-performance beam steerer in one chip. However, the resolution of InP-based beam steerers has been limited by their aperture size [18]. Conventional waveguides based on InP are weakly confined, which makes large-scale integration (thus large aperture) challenging. Furthermore, due to the thick cladding layers, it is difficult to produce efficient GAs on the conventional InP platform.

By substituting the high-index InP cladding with low index dielectrics, the InP membrane on silicon (IMOS) platform can offer both the complete functionalities of InP and the compactness of SOI [19]. The higher optical confinement in membrane compared to conventional InP allows stronger light-matter interaction, allowing for enhanced efficiencies in PMs and SOAs [20]. Furthermore, a larger field of view (FoV) can

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also be realized through dense integration of highly confined, small footprint membrane photonic components.

Since the beam divergence in the far-field is related to the emission aperture size by a Fourier transform, the bigger the emission aperture, the finer the emitted beam. For a single constant-pitch, constant-filling-factor GA, the emission aperture is primarily proportional to the effective grating length, where the light intensity along the GA drops to 1/e² of the original value. To achieve a < 0.1° FWHM divergence, a mm-long GA is required. Fiber grating couplers (FGC) on the IMOS platform with a shallow etch depth of 120 nm normally have an effective length around 10 µm, which is only a fraction of what is required. With the shallow etch scheme, in order to yield a < 0.1° FWHM for the emitted beam, a < 10 nm etch depth is required. Such nanometer-scale shallow etching is not fabrication tolerant in terms of etch depth control and etch uniformity. A novel design is needed to tackle this challenge.

In this paper, we demonstrate high-resolution beam steers through novel fabrication-tolerant GAs on the IMOS platform for the first time. The paper is divided in two parts: First half of the paper is about the design where the concept and parameter optimization are described, and the second half explains device fabrication and measurement including both far-field and near-field analysis.

II. THE WEAK COUPLING GRATING ANTENNA DESIGN

A. Design concept

We propose a grating antenna scheme in which low index contrast gratings is made in the SiO₂ super-cladding on top of the high confinement InP membrane waveguide, thus offering simultaneously high fabrication tolerance, narrow FWHM and potentially high integration density to achieve large FoV.

A 1-D GA has been designed, as seen in Fig. 1. The GA has a width of 15 µm, and is tapered down to 400 nm, then connected to input/output FGCs at both ends. A metal mirror made of Ti/Au/Ti underneath the GA is used to increase the emission efficiency and improve the fabrication robustness, as the constructive interference condition can be met accurately and uniformly across the wafer by controlling the thickness of SiO₂ buffer, regardless of the BCB thickness which is more difficult to control. The Ti layers on both sides increase adhesion to both wafers in the bonding process. The thickness of the SiO₂ super-cladding and the InP membrane are 100 nm and 300 nm, respectively.

Fabrication tolerance is crucial for photonic integrated circuits (PIC) to make them suitable for mass production. For GAs, the most significant critical dimension variation (CDV) comes from the etch depth variation in the gratings. This CDV can exist in at least two forms: the nonuniformity of the etch depth induced by lag effect during plasma etch [21], and the grating depth variation induced by etch rate fluctuation across different batches. One way to obtain good fabrication tolerance is to add an etch-stop layer at the desired depth beforehand, and then apply over-etch to clear the footing and reduce the lag effect [22]. Over-etch also produces a safe margin where small fluctuations in the etch rate or etch time can be tolerated.

As can be seen in Fig. 2(b), in our design, instead of an additionally deposited etch stop layer, the top surface of the InP membrane can naturally serve as an etch stop, since InF₅, one of the etch product of the Florine-based chemistry for SiO₂ etching, is highly non-volatile. We have experimentally tested the penetration of our SiO₂ etching recipe on InP, and the result is plotted in Fig. 2(a). The 1 nm/min penetration in InP delivers a 30:1 (SiO₂:InP) etch selectivity, yielding a well-controlled etch depth in the GA. The slow penetration rate in InP also enables minute-scale tolerance in etch time control, bringing a more relaxed and reproducible fabrication process compared to shallowly etched gratings on IMOS.

B. Design optimization

The GA concept has been simulated by 2-D finite difference time domain (FDTD) method to achieve a working design. Two parameters have been studied: the SiO₂ buffer thickness and the pitch of the GA. In order to improve time efficiency of the simulation, only a length of 60 µm has been simulated. In our design, 2nd order gratings (grating pitch is equal to the wavelength in the grating area) have been used, since they theoretically produce only one grating diffraction order. The far-field emission follows the grating equation:

\[
\sin \theta = n_{eff} \frac{\lambda}{A},
\]

where \( \theta \) is the angle of emission, \( n_{eff} \) is the effective refractive index in the grating area, \( \lambda \) and \( A \) are the wavelength and grating pitch, respectively.

Fig. 3(a) shows the relation of the coupling efficiency of the GA to free-space modes and the absorption loss introduced by metal as a function of the thickness of the SiO₂ buffer. The
coupling efficiency has been normalized to 1 and the wavelength in simulation is 1550 nm. As seen in Fig. 3(a), two peaks can be found in the coupling efficiency at the buffer thicknesses of 50 nm and 580 nm, which correspond to the 1st and 2nd resonance peaks of the Fabry-Perot (FP) cavity between the GA surface and the metal mirror. In the case of a mm-long GA, the metal absorption loss will be substantial if the mirror is placed too close. Therefore, a 580 nm buffer thickness producing 2nd order resonance has been chosen, where the metal absorption loss has already dropped to negligible values.

\[ \text{Efficiency Imbalance (dB/cm)} \]

<table>
<thead>
<tr>
<th>Grating Pitch (nm)</th>
<th>Efficiency Imbalance (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>0.70</td>
</tr>
<tr>
<td>575</td>
<td>0.75</td>
</tr>
<tr>
<td>580</td>
<td>0.80</td>
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<tr>
<td>600</td>
<td>0.85</td>
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<tr>
<td>625</td>
<td>0.90</td>
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<tr>
<td>650</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The filling factor \( k \) of the gratings is determined to be integrated with an on-chip tunable laser in the future, the co-design becomes important. Typical tuning range of on-chip widely tunable lasers with a center wavelength of 1550 nm, is 60 nm [23], within which our GA should be capable of emitting light efficiently. Having found a proper buffer thickness, a parameter sweep has been performed on the grating pitch, in the wavelength range of 1520 nm – 1580 nm. The wavelength-averaged coupling efficiency and the wavelength-dependent efficiency imbalance are shown in Fig. 3(b), where an optimal pitch value of ~ 600 nm can be found, yielding the highest average coupling efficiency and the lowest imbalance. Here the coupling efficiency has also been normalized to 1 for better visualization, since the simulated region is only 60 µm, where out-coupled optical power is only a fraction of the real device. Note that the imbalance is only ~ 0.7 dB for a 60 nm wavelength tuning range, indicating the broadband nature of our GA. The kinks around 570 nm pitch are due to the Bragg reflections, as can be seen in Fig. 3(c). In general, the Bragg conditions have to be avoided since they create reflection which may be detrimental to other on-chip components, especially tunable lasers.

To validate our design, the device parameters have been tested in a 1-mm long GA scenario with 2-D FDTD simulation. Fig. 3(a) shows the device parameter optimization by 60 µm long antenna with FDTD simulation. (a): Waveguide loss and normalized average coupling efficiency in the wavelength range of 1520 nm – 1580 nm with varying buffer thickness. (b): Normalized average coupling efficiency and imbalance of the coupling efficiency in the wavelength range of 1520 nm – 1580 nm with varying grating pitches. (c): The reflectivity of GAs with varying pitches at different wavelengths showing evidence of Bragg condition around a pitch of 550 nm – 580 nm.

Fig. 3. Device parameter optimization by 60 µm long antenna with FDTD simulation. (a): Waveguide loss and normalized average coupling efficiency in the wavelength range of 1520 nm – 1580 nm with varying buffer thickness. (b): Normalized average coupling efficiency and imbalance of the coupling efficiency in the wavelength range of 1520 nm – 1580 nm with varying grating pitches. (c): The reflectivity of GAs with varying pitches at different wavelengths showing evidence of Bragg condition around a pitch of 550 nm – 580 nm.

Fig. 4. The emission angle, coupling efficiency and logarithmic plot of the far-field pattern of a 1-mm long grating antenna with input wavelength tuning from 1520 nm - 1580 nm. (a): Angle of emission and coupling efficiency of the out-coupled light at different wavelengths. (b): Logarithmic far-field intensity pattern of the grating antenna at different wavelengths (plotted in different colors).

Fig. 4. The emission angle, coupling efficiency and logarithmic plot of the far-field pattern of a 1-mm long grating antenna with input wavelength tuning from 1520 nm - 1580 nm. (a): Angle of emission and coupling efficiency of the out-coupled light at different wavelengths. (b): Logarithmic far-field intensity pattern of the grating antenna at different wavelengths (plotted in different colors).

The strength of the gratings can be quantified in the coupling strength \( \kappa \). For uniform and lossless gratings, the light intensity
along the GA follows this equation:
\[ I(z) = I(0)e^{-2\kappa z}, \]
in which \( \kappa \) is the length where the amplitude in the GA has dropped to 1/e of the input. The filling-factor-dependent coupling strength for our GA has been obtained by 2-D FDTD simulation, as seen in Fig. 5. In our 1-mm design the filling factor used was 0.5, which corresponds to the highest \( \kappa \) for our SiO₂ based GA. Therefore, it is possible to achieve longer antennas and narrower beams by decreasing or increasing the filling factor to obtain even weaker grating coupling strengths. Furthermore, we have also designed an improved grating antenna with further improvement of the far-field beam width. The improved design uses a filling factor of 0.8, resulting an extremely weakly coupled grating antenna of 2 mm in length.

Finally, a resist removal process was applied to expose the fabricated devices.

The fabricated devices are shown in Fig. 6. As can be seen, the metal mirrors are tilted at the ends to reduce possible reflections induced by effective refractive index mismatch.

B. Measurement

A special setup has been built for direct characterization of the far-field pattern of our GA. As seen in Fig. 7, the infrared camera (Xenics, 320 × 256) was attached to a rotatable “crane” with adjustable height. The inclination angle of the crane was controlled by a high torque stepper motor, which was connected to a sensor displaying absolute angle readings. Therefore, the captured image can be easily transformed into spherical coordinates, since the camera was fixed and the pixel size is known. By adjusting the table height, the emission from the GA was made concentric with the rotation path of the camera. In order to ensure a sufficient quality of the far-field image, the distance from the camera sensor to the GA was set to 52 cm, a value where sufficient details on the main-lobe can be preserved, while the background emission can still be imaged in the camera aperture.

Fig. 5. Simulated grating coupling strength with varying filling factors.

Fig. 6. Fabricated waveguide grating antennas on IMOS. (a): Close-up image of the grating antenna, the access taper and the underlying metal mirror. (b): SEM image of a GA with 0.8 filling factor showing details on the gratings. (c): Microscope image of an array of GAs with different lengths.

Fig. 7. Schematic of the measurement setup (illustrative, not-to-scale). The distance between the camera and the device under test is measured from the camera sensor to the wafer upper surface.
The input light was generated by a widely tunable laser (Keysight, S+C bands), and then fed into one of the input FGCs with a single mode fiber (SMF). Then, the camera was swung in a certain range to record the far-field images. The FWHMs were then extracted from the images by a Gaussian curve fit. To study the FWHM performance with different aperture sizes, we have measured an array of GAs with a filling factor of 0.8 and varying total lengths, at the same input wavelength of 1557 nm. As can be seen in Fig. 8 (a), starting from over 0.4° at a length of 0.2 mm, the FWHM rapidly decreases with increasing GA length, falling under 0.1° at a length of 0.8 mm. The narrowest FWHM of 0.05° was obtained at a length of 2 mm. To the best of our knowledge, this is the narrowest experimentally demonstrated FWHM in InP-based beam steers to-date. No higher-order mode was observed in the far-field, due to the 2nd order gratings made possible by our high resolution EBL.

Measured signal-to-noise ratio (SNR) is over 10 dB, as seen in Fig. 8(b). The SNR can be further improved by apodization to obtain a more uniform near-field emission, but it is beyond the scope of this paper. The out-of-plane intensity distribution has also been characterized using the same far-field setup, as seen in Fig. 8(c). The intensity profile matches well with the gaussian shape, which is as expected since there is only one emitter in the out-of-plane direction.

![Far-field measurement on the GAs with a filling factor of 0.8 showing the FWHM characteristics. (a): FWHM of the GA with varying length. Area shaded in green indicate the < 0.1° regime. (b): Far-field image of the GA showing a record-narrow FWHM of 0.05° at a length of 2 mm. Black dots: measurement data points. Red line: Gaussian fit of the measurement data. (c): Out-of-plane intensity distribution of the GA showing a FWHM of 7.39°. Black dots: measured data points. Red line: Gaussian fit of the measured data.](image1)

![Steer map of the GA from 1505 nm to over 1610 nm. The maximum intensity has been normalized to 1. Insets: zoomed-in figures of the captured far-field images near 1557 nm and 1511 nm.](image2)

The steer map of the GA with a 0.8 filling factor and 2-mm length was measured using the same setup at different wavelengths, as seen in Fig. 9. An angular FoV of 13.5° was observed over a wavelength tuning range from 1503 nm – 1615 nm (the limit of our tunable laser). This > 100 nm wavelength working range is much larger than those of typical on-chip tunable lasers (60 nm), indicating the broadband operation and a good integration compatibility of our GA. The intensity decrease near the wavelength limits are due to the input FGCs, which have a typical 3 dB bandwidth of 60 nm – 70 nm. The combination of a narrow beam and a wide FoV yields a high resolution of more than 250 resolvable points, which is defined by FoV/FWHM.

![Steer map of the GA from 1505 nm to over 1610 nm. The maximum intensity has been normalized to 1. Insets: zoomed-in figures of the captured far-field images near 1557 nm and 1511 nm.](image3)

![Near-field measurement of the GA showing the relation between intensity and length. GA with 0.5 filling factor is shown for comparison. The logarithmic plot and linear fitting of the experimental data points shows an exponential relation.](image4)

To achieve a better understanding of our GAs, we have also carried out near-field measurements. This measurement involved two SMFs. One SMF for light input was kept at optimal coupling condition with the FGC, while the other was...
scanning along the GA surface to collect the near-field locally. The collected light was then sent to a photodetector. The distance between the scanning SMF and the GA surface was kept minimum without physical touching to obtain maximum measurement accuracy. We have measured GAs with both filling factors of 0.8 and 0.5, as can be seen in Fig. 10. As expected, near-field intensities of both GAs exhibited a characteristic of exponential decay, and the 0.5 filling factor GA showed a faster decay rate than the 0.8 filling factor GA. The grating coupling strengths $\kappa$ were extracted by linearly fitting the near-field intensity in logarithmic plots, as seen in Fig. 10. The fitted $\kappa$ for 0.5 and 0.8 filling factors were 1.55 mm$^{-1}$ and 3.75 mm$^{-1}$, which indicate mm-long effective lengths, around 100 $\times$ of conventional shallow-etched grating couplers on IMOS. Note that this is the loaded $\kappa$ combining effect of waveguide loss, metal absorption and grating out-coupling. Since the metal was kept far away from the waveguide and the waveguide width was 15 $\mu$m wide, both loss figures should be low. Therefore, we could use the loaded $\kappa$ to approximate real $\kappa$ values. The higher measured $\kappa$ compared to simulation results shown in Fig. 5 may have two contributing factors: (1) The FDTD simulation was 2-D, but in reality the device was 3-D; (2) The 1.5 minute over-etch brings 1.5 nm penetration into the high-confinement InP waveguide leading to slightly stronger coupling.

IV. CONCLUSION

We have proposed a novel InP-based grating antenna scheme for optical beam steering. The SiO$_2$-on-InP based gratings not only offers high performance, but also good fabrication tolerance and compatibility with InP-based active components. Design parameters of the grating antenna have been explored and optimized, yielding a high-resolution, broadband design. Measurement results on the grating antenna have shown a record-narrow FWHM of 0.05$^\circ$ and high resolution of more than 250 points with a 2-mm long grating antenna. Therefore, this work contributes an important building block towards a densely-integrated high resolution InP-based beam steerer, which may properly address the growing market demand in the future.

REFERENCES


Yi Wang obtained the B.Sc. degree in 2015 and the M.Sc. degree in 2018 from the Sun Yat-sen University in Guangzhou, China. He is currently a Ph.D. candidate at the Eindhoven University of Technology, the Netherlands. His current research interests include optical beam steering, high efficiency SOAs and active/passive integration.

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Zizheng Cao is currently a tenured assistant professor with ECO group at Institute for Photonic Integration (IPI) of Eindhoven University of Technology (TU/e), the Netherlands. In 2015, he was graduated with highest honor PhD degree (cum laude) in Eindhoven University of Technology. After one-year post-doctoral research, Dr. Cao has been appointed an assistant professor in TU/e. Dr. Cao has more than 10-year research experience on optical communication system design, high speed digital signal processing, and the design, fabrication and characterization of photonics integrated circuit in multiple platform including SOI, SiN and InP. His current research interests include, a) indoor optical communications, b) microwave photonics, c) photonic integration. He is a recipient of IEEE Photonics Society Graduate Student Fellowship 2014. He serves for European Conference on Optical Communication (ECOC) as a member of technical program committee (TPC). He serves as an active reviewer for many IEEE/OSA journals. He received the Graduate Student Fellowship of the IEEE Photonics Society 2014.

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Institute, Berlin, Germany, within the Department of Photonic Components. Since 2018, he is with the newly established Photonic Integration Technology Centre (PITC) of the Eindhoven University of Technology, where he is the Technology Development lead. He has a strong expertise in III-V photonic integrated circuits (PIC) technology, both on generic and membrane-based platforms. At the PITC, he is mainly engaged with development activities in cooperation with industry partners with the aim to increase the technology readiness level (TRL) of InP PIC technology through open innovation. He also keeps a part-time appointment at the Institute for Photonic Integration (IPI, former COBRA Research Institute), where he is involved in novel research, such as nanolasers for neuromorphic applications and applied research of PIC-based sensors with particular focus on LiDAR.

Kevin Williams received the B.Eng. degree from the University of Sheffield, Sheffield, U.K., and the Ph.D. degree from the University of Bath, Bath, U.K., in 1995. He moved to the University of Cambridge, Cambridge, U.K., in 2001 and was elected Fellow at Churchill College. His research interests are in the area of integrated photonic circuits. He was the recipient of a Royal Society University research fellowship at the University of Bristol, Bristol, U.K., in 1996. In 2006, he was the recipient of a European Commission Marie Curie Chair at the COBRA Institute, now known as the Institute for Photonic Integration at the Eindhoven University of Technology, The Netherlands. In 2011, he was the recipient of a Vici award from the Netherlands Organization for Scientific Research, where he has focused on photonic integration technology. He is the chair of the Photonic Integration research group at Eindhoven University of Technology.

Yuqing Jiao was born in Hangzhou, China. He obtained double PhD degrees from both Eindhoven University of Technology, the Netherlands, and Zhejiang University in China in 2013. Since then he continued his research at Eindhoven University of Technology. Since 2016 he is appointed as an Assistant Professor at the Institute of Photonic Integration (IPI, former COBRA Research Institute) of the Eindhoven University of Technology. His research topic is focused on a novel III-V based nanophotonic platform. He is focusing on ultrafast and strong light-matter interactions in sub-micron optical confinement. Applications span from optical interconnects, ultrafast photonic devices, to optical beam steering and optical sensing. He has strong background and expertise in a wide range of photonic materials (from silicon to III-V) and nanotechnologies. He has (co-)authored one book chapter in the Semiconductors and Semimetals (Elsevier), more than 30 international journal publications and 80 conference papers. These include invited journal papers in the IEEE Journal of Selected Topics of Quantum Electronics, Journal of Lightwave Technology and SCIENCE CHINA Information Sciences, as well as 8 invited talks in top international conferences. He is a member of the IEEE Photonics Society and the Optical Society of America. Currently he serves as a board member of IEEE Photonics Society Benelux Chapter.