Optical phased array for sub-Doppler spectroscopy of the rubidium D2 absorption line

Jeremi Januszewicz*, Eugenio Di Gaetano*, Zack McConkey*, Martin Sinclair*, Ugnė Hawley*, Sean Dyer†, James McGilligan†, Paul F. Griffin†, Erling Riis†, Marc Sorel*, Douglas J. Paul* and Kevin Gallacher*

*University of Glasgow, James Watt School of Engineering, Rankine Building, Glasgow, G12 8LT, U.K.
†Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, U.K.

***Abstract*—We present a novel approach of interfacing photonic integrated circuits with wafer-bonded MEMS vapour cells leveraging the silicon fabrication techniques for size, weight, power and cost reduction of miniature atomic systems.**

I. Introduction

Light-atom interaction such as absorption due to excitation of the hyperfine energy levels in reference atoms serves as a basis for quantum sensors and cold atom systems which enable precise measurements of time, magnetic field and rotation and provide a position, navigation and timing reference for critical infrastructure [1]. Although miniature atomic devices based on discrete components are commercially available, photonic integrated circuits (PICs) offer an advantage for mass manufacturing by leveraging lithography and limiting the need for precise optical alignment [1].

Coupling the waveguide-confined optical mode with atoms in a micro-fabricated MEMS vapour cell is a crucial challenge for the PIC integration of atomic systems. Evanesce sensing approaches such as atomic-cladding waveguides [2] allow easy integration with MEMS cells, however, are largely limited by transit time broadening of the atomic absorption due to small optical overlap with the atomic vapour. Narrower absorption profiles can be observed by delivering a sufficiently large beam to the vapour cell, as was recently shown with the extreme mode-converting apodized gratings [3].

We are proposing an alternative approach, utilising optical phased arrays (OPA) to convert the sub-micron optical mode to a $128\,\mu\mathrm{m}$ wide beam in free space. Our approach benefits from simple, fabrication tolerant and scalable design and leaves scope for further work on beam shaping and beam steering. Even with a non-Gaussian emission profile, it allowed us to experimentally record the hyperfine splitting of the rubidium D2 line. We are planning to leverage the well-understood beam steering capabilities of OPAs to create fabrication tolerant, single chip saturated absorption spectroscopy PICs for laser stabilisation [4] that would improve the performance of miniature atomic clocks and contribute to the size, weight, power and cost reduction of cold atom systems [1].

II. Design

The OPA is designed to emit a $128\,\mu\mathrm{m}$ wide beam, providing enough optical overlap to resolve the $6\,\mathrm{MHz}$ hyperfine splitting of the rubidium D2 absorption line that is of interest for laser cooling and cold atom trapping [1]. We chose the $200\,\mathrm{nm}$ thick Si_3N_4 on SiO_2 platform for single-mode operation at $780\,\mathrm{nm}$ wavelength and to maintain compatibility with previously demonstrated polarisation rotators and polarising beam splitters [4].

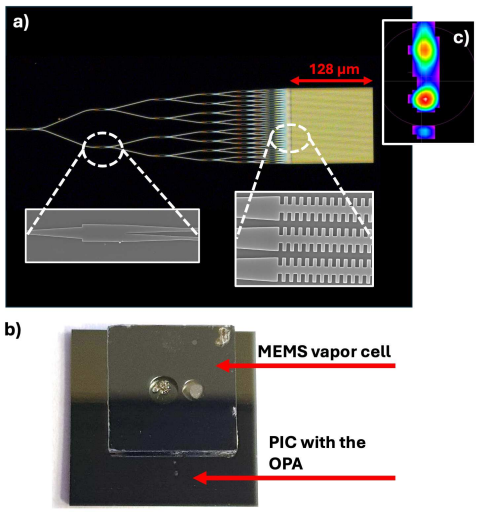

Fig. 1. a) Darkfield microscope image of the optical phased array (OPA) with high magnification SEM images of the MMI coupler and grating antenna as insets. b) Proposed integration method of a MEMS vapour cell with photonic integrated circuits by flip chip bonding. c) Far-field beam profile of the OPA recorded experimentally.

We used a splitter tree of 63, 1x2, multi-mode interference (MMI) couplers to feed a uniform, non-apodized antenna array of 64 Bragg sidewall grating waveguides. The MMIs were optimised for the wavelength of interest by utilising a particle swarm optimisation algorithm. The insertion loss of the splitter tree was simulated to be $< 1\,\mathrm{dB}$ with a single MMI loss of $0.015\,\mathrm{dB}$.

Gratings are $1.5\,\mu\mathrm{m}$ wide, providing enough mode confinement to obtain $< 1\%$ coupling between the gratings at $\lambda/2$ antenna spacing which helps to suppress the antenna sidelobs hence reducing the loss. The far-field emission profile resulting from exponential emission along the uniformly fed antenna array can be seen in Figure 1 c).

We fabricated the device in-house on a silicon substrate with $4\,\mu\mathrm{m}$ of thermal SiO_2 and $200\,\mathrm{nm}$ LPCVD Si_3N_4 by electron-beam lithography and C_4F_8 reactive ion etching of the Si_3N_4 film followed by PECVD SiO_2 cladding layer deposition.

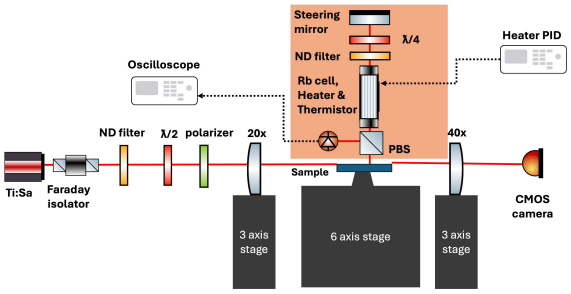

Fig. 2. Measurement set-up for saturated absorption spectroscopy with beam delivered from a photonic integrated circuit including an optical phased array.

Facets were formed by diamond saw dicing followed by facet polish. Fabricated device can be seen in the Figure 1 a). The intended use case with a MEMS vapour cell flip-chip bonded to the cladding layer is presented in Figure 1 b).

III. Spectroscopy

When in a vapour state, atomic absorption profiles experience Doppler broadening due to random movement of gas particles, which obscures the hyperfine splitting of the excited state. The absorption resulting from the excitation of the hyperfine energy levels can be resolved by utilising saturated absorption spectroscopy (SAS).

SAS is a pump-probe technique, where the pump beam saturates the optical transition such that the counter-propagating probe beam can no longer be absorbed when interacting with atoms that have zero velocity along the laser beam. This results in dips corresponding to the hyperfine splitting, superimposed on the Doppler broadened absorption profile.

To verify our design, we used the OPA for beam delivery into a free-space SAS set-up utilising a $7.5\,\mathrm{cm}$ long glass vapour cell as shown in Figure 2. This allowed us to record the hyperfine splitting of the $\left|5S_{1/2}, F_g = 2\right\rangle \rightarrow \left|5P_{3/2}\right\rangle$ absorption in ^{87}Rb which can be seen in the Figure 3. As a proof of concept this measurement was repeated with a $1\,\mathrm{mm}$ long MEMS vapour cell [5]. The corresponding absorption can be seen in Figure 3 b). This shows that a simple, non-apodized $\lambda/2$ OPA is sufficient to resolve the hyperfine splitting of the rubidium D2 line.

IV. Conclusion

We have demonstrated a novel approach to single-chip light-atom coupling enabling sub-Doppler spectroscopy of the rubidium vapour. With MEMS rubidium vapour cells [5], polarisation control [4], high-Q ring resonators [6] and narrow linewidth, $780.24\,\mathrm{nm}$ lasers [7] previously demonstrated we believe this is a step towards single-chip integration of atomic systems.

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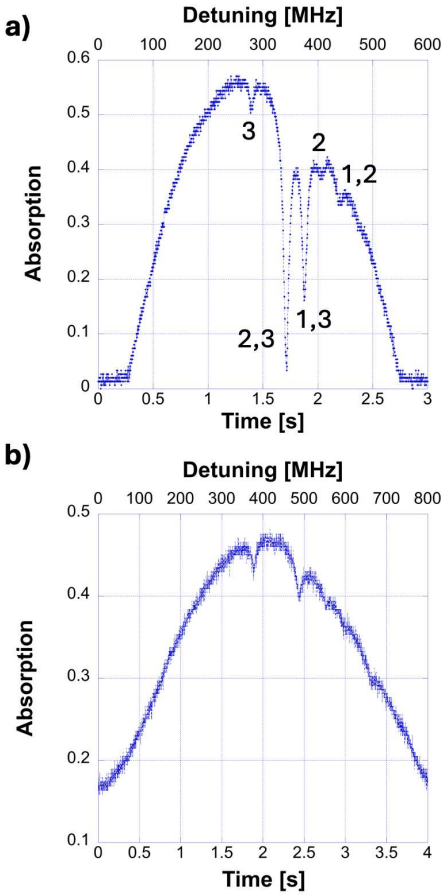

Fig. 3. Normalised absorption of the $\left|5S_{1/2}, F_g = 2\right\rangle \rightarrow \left|5P_{3/2}\right\rangle$ transition vs the laser scan time recorded by saturated absorption spectroscopy (SAS) utilising the optical phased array (OPA) for beam delivery. a) SAS utilising a glass vapour cell, numbers labelling hyperfine levels F_e. b) SAS utilising a MEMS vapour cell.

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