Silicon-Nitride Photonic Integrated Circuits for Atomic Systems

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***Abstract*—We present the development of a silicon-nitride photonic integrated circuit platform aimed at a range of miniature atomic systems including atomic clocks and cold atom sensors which includes narrow-linewidth ($\leq$3.7 kHz) distributed feedback lasers and wafer-bonded MEMS rubidium vapour cells.**

***Index Terms*—photonic integrated circuits, atomic systems**

Miniature atomic systems are already commercially available in the form of chip-scale atomic clocks (CSACs) [1] but a whole host of other applications including atomic magnetometers and cold atom accelerometers, gravimeters and gyroscopes could be mass produced if suitable microfabrication and integration techniques can be developed [2]. These initial CSACs have limitations with accuracies of $\leq$ 1 µs per day but optical atomic clock architectures which could be engineered to be chip scale with accuracies of $\leq$ 1 ns per day have been proposed [3]. To achieve such systems a range of components must be integrated which include narrow-linewidth lasers at specific atomic transitions [4]–[6], spot-size converters (SSC), optical isolators, phase and amplitude modulators, polarizing beam-splitters (PBS) [7], polarization rotators (PR) [7], high-Q micro-resonators [8], miniature frequency combs, grating couplers, photodetectors and MEMS vapour cells [9] to contain the required atomic species.

Here we present the development of a Si_3N_4 photonic integrated circuit (PIC) platform [7] [8] suitable for a wide range of thermal and cold atom atomic systems which includes integrated III-V distributed feedback (DFBs) lasers [4]–[6] and Rb MEMS vapour cells [9]. The waveguides are 200 nm thick Si_3N_4 grown by low pressure chemical vapour deposition deposited on 4 µm thermal SiO_2 with a 1.5 µm plasma enhanced chemical vapour deposition cladding [8]. A schematic diagram of an example PIC for saturated absorption spectroscopy to lock lasers to atomic transitions is presented in Fig. 1. Also shown are images of developed components included DFB lasers flip-chip bonded to a Si chip and aligned to SSCs that couple the light into Si_3N_4 waveguides on the chip, PBS, PR and a MEMS Rb cell which can be wafer bonded to the PIC. The MEMS Rb vapour cells have recently been used to lock lasers enabling chip-scale laser cooling of atoms [9].

A key part of such atomic systems are narrow-linewidth lasers. We have chosen Rb atoms so lasers at 780.2 nm and 795.0 nm are required for systems using the D2 and D1 transitions respectively where lasers with linewidths below

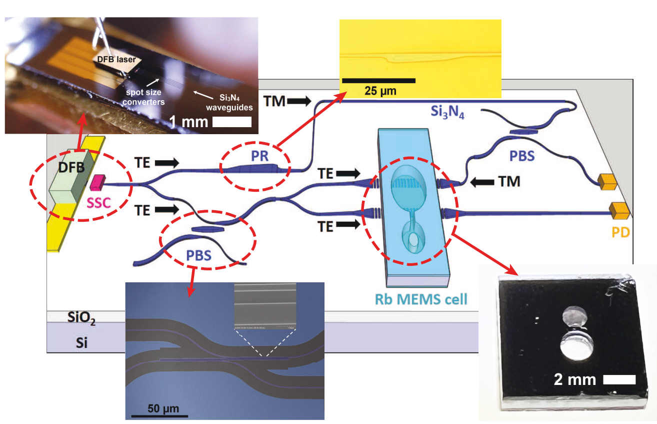

Fig. 1. A schematic diagram of a saturated absorption spectroscopy PIC to lock a laser to an atomic transition in an integrated MEMS vapour cell as required for a range of atomic systems.

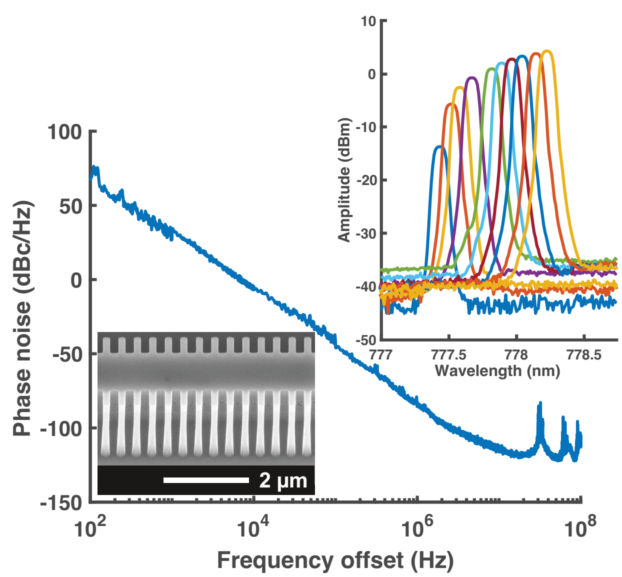

Fig. 2. The phase noise of a free-running 778.1 nm DFB laser as a function of offset frequency providing a Lorentzian linewidth of 3.7 kHz over 25 µs integration time. Insert left: A SEM image of the DFB grating. Insert right: The laser output amplitude when the current is tuned from 120 mA to 300 mA in 20 mA steps.

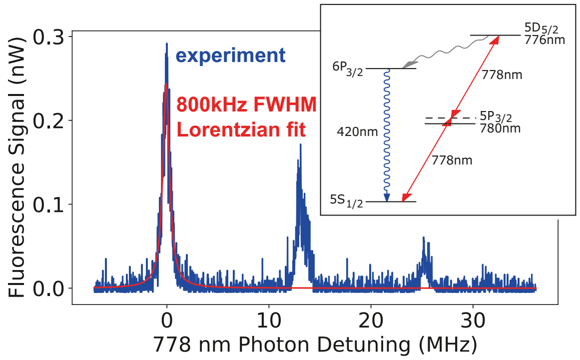

Fig. 3. A two-photon spectroscopy scan using a free-running DFB laser. Insert: The atomic states and transitions in the two-photon spectroscopy.

the natural linewidths of 5.7 MHz are required. For more accurate clocks the Rb 2-photon transition at 778.1 nm with a 322 kHz linewidth requires lasers with linewidths well below

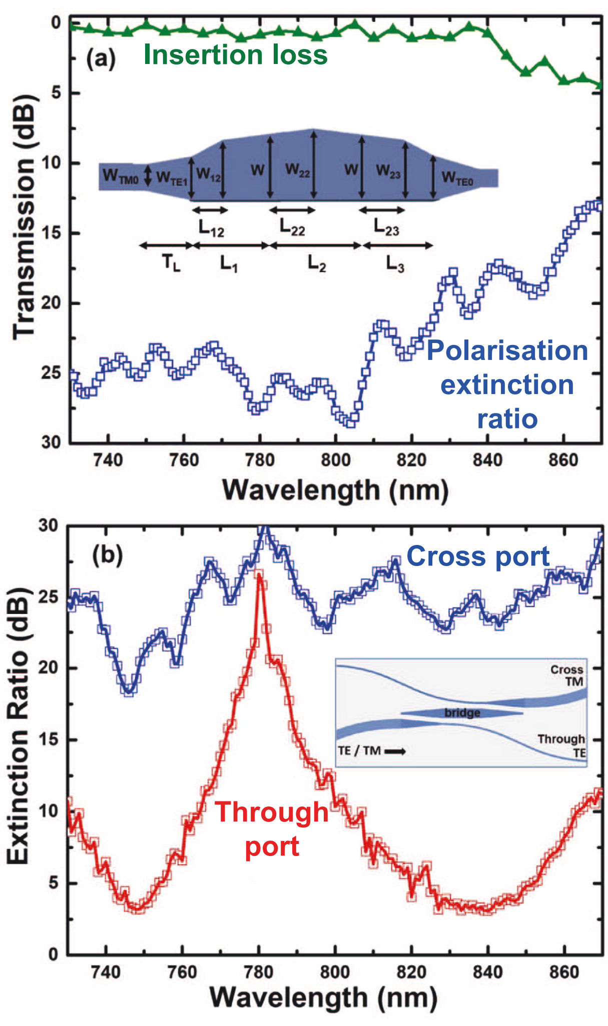

Fig. 4. (a) The experimental insertion loss and polarization extinction ratio as a function of wavelength for the PR and (b) the polarization extinction ratio for the cross and through ports of the PBS presented in Fig. 1.

this value. Figure 2 demonstrates a 778.1 nm DFB laser [6] with power >48 mW, mode-free hop tuning range of $\geq$1 nm, side-mode suppression ratio $\sim$ 40 dB, a low random intensity noise of -150 dBc/Hz and linewidths of 3.7 kHz (226 kHz) over integration times of 25 µs (100 ms). To demonstrate that this laser is suitable for atomic systems, we have undertaken 2-photon spectroscopy [6] on a quartz cell containing Rb as demonstrated in Fig. 3.

Key for undertaking saturation absorption spectroscopy using a single PIC is the ability to control the polarization of light in both waveguides and in PBS. We have demonstrated PR (Fig. 4(a)) and PBS (Fig. 4(b)) with polarization extinction ratios above 27 dB with insertion losses <0.5 dB at 780 nm wavelength [7]. Whilst these devices are demonstrated at 780 nm wavelength, it is easy to modify the designs for high performance at wavelengths corresponding to suitable atomic transitions for Rb, Li, Cs, K or Sr.

To conclude, the development of a Si_3N_4 PIC platform suitable for a wide range of thermal and cold atom atomic systems which includes integrated III-V DFBs lasers and Rb MEMS vapour cells has been presented.

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