Distributed Feedback Lasers for Quantum Cooling Applications

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ABSTRACT

There is an ever-growing need for compact sources which can be used for the cooling process in high accuracy atomic clocks. Current systems make use of large, expensive lasers which are power-hungry and often require frequency doubling in order to hit the required wavelengths. Distributed feedback (DFB) lasers have been fabricated at a number of key wavelengths which would allow chip scale atomic devices with very high accuracy to become a reality. Two key atomic transitions analysed here are $^{88}Sr^{+}$ and ^{87}Rb which require cooling at 422 nm and 780.24 nm, respectively. The vital parameter of the DFB lasers for this application is the linewidth, as very narrow linewidths are required in order for the atomic cooling process to occur. The lasers realised here produce the required power levels, with high side-mode suppression ratios and show good single mode tuning which is important for hitting precise wavelengths. This work will present the latest techniques and results using the DFB lasers at both wavelengths.

1. INTRODUCTION

Atomic clocks, which are based on cold-atom systems, rely on very accurate measurements where a laser is locked to a stable atomic transition [1]. As these devices require extremely high accuracy, the lasers which are used must be optimised in terms of linewidth, stability, wavelength and output power. Currently, many systems make use of large, expensive, power-hungry laser systems [2]; however semiconductor lasers offer a less expensive, chip-scale alternative. Semiconductor lasers can be easily integrated with other components and offer a much lower power consumption [3] which is desirable for the realisation of compact atomic clocks [4]. Single frequency lasers or distributed feedback (DFB) lasers are presented here which offer a solution. This work looks at two key atomic transitions: Strontium ($^{88}Sr^{+}$) which requires laser cooling at 422 nm, and Rubidium (^{87}Rb) which requires cooling at 780.24 nm. The DFB lasers have been designed, fabricated and characterised to hit the specifications required for use in atomic clocks.

2. DESIGN AND FABRICATION

The devices at both wavelengths follow similar designs to optimise their performance for these applications, although there are some key differences between the different materials. A detailed description of the fabrication processes can be found in [5] for the GaAs DFBs and in [6] for the GaN DFBs. The Schawlow-Townes formula allows us to see how the design parameters will ultimately affect the laser linewidth [7].

$$\Delta\upsilon = \Gamma_{QW}\frac{r_{sp}}{R_{sp}}\frac{h\upsilon(\alpha_i+\alpha_m)\alpha_m(1+\alpha_H)^2}{4\pi P_{out}}$$

This equation shows that in order to have a laser with a narrow linewidth ($\Delta\upsilon$), it is required to have low propagation losses (α_i), low mirror losses (α_m), low mode confinement in the active quantum well region (Γ_{QW}), and a low Henry factor or linewidth enhancement factor (α_H). Also, narrower linewidths can be achieved by increasing the power output (P_{out}) of the laser. The photon energy ($h\upsilon$) and the spontaneous emission fraction (r_{sp}/R_{sp}) can be assumed as fixed terms.

The Bragg grating design can be optimised by focussing on two parameters: the coupling factor, κ, and the cavity length, L. The product, κL, is the total grating coupling and determines the modal gain threshold. This value should be optimised to ensure stable single mode operation as well as a low threshold value and narrow linewidth. Figure 1 shows the scanning electron microscope (SEM) images of the different gratings that have been fabricated for the different materials. Ultimately, the design of DFB lasers is a compromise between high power, narrow linewidth, low threshold and a low divergence angle.

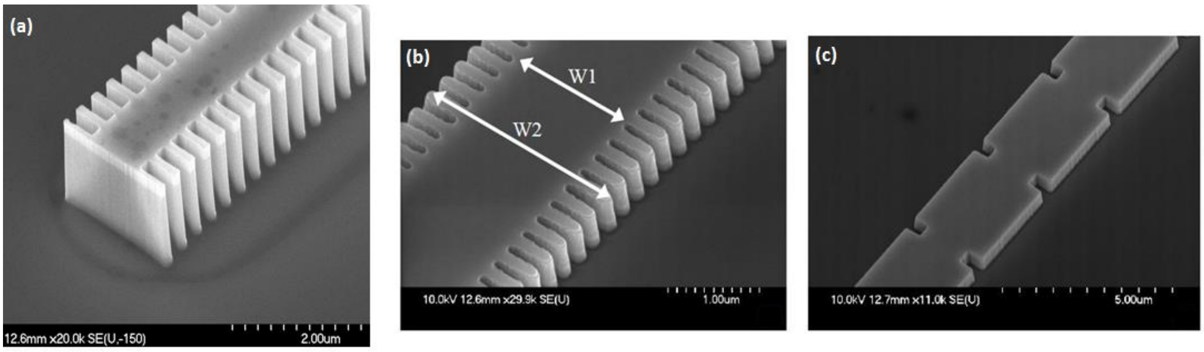

Figure 1 SEM images showing (a) a 3rd order grating GaAs DFB laser, (b) a 3rd order grating GaN DFB laser and (c) a 39th order grating GaN DFB laser.

3. CHARACTERISATION

The key parameters for each of the devices were measured to understand the laser performance. The light-current-voltage (LIV) and spectral properties are analysed as well as the linewidth of the lasers. Figure 2(a) shows the LIV characteristic of a GaAs laser at 20°C. This shows a threshold current of 140 mA with a voltage bias lower than 2 V up to 250 mA, which demonstrates a good electrical conductivity in the epilayer. Powers in excess of 60 mW were achieved, with kink-free behaviour shown in the L-I plot between the threshold current and up to 240 mA. The optical spectrum of the DFB laser was measured as a function of drive current and is shown in Figure 2(b), again at 20°C. The DFB clearly exhibits single mode behaviour and hits the desired wavelength of 780.24 nm, with no mode hopping apparent. A side-mode suppression ratio (SMSR) of over 40 dB is seen here.

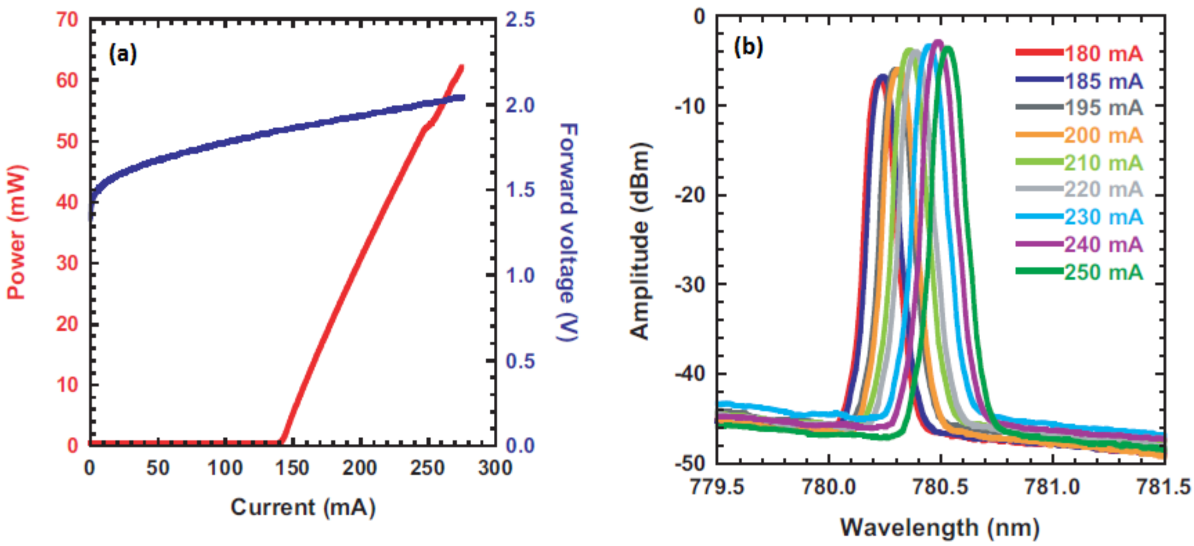

Figure 2(a) LIV and (b) spectra for a GaAs DFB laser.

The linewidth of the laser was characterised using the heterodyne detection technique [8]. Light from a commercial Ti:Sapphire laser, with a known linewidth of 50 kHz, was beat with the light from the DFB laser and coupled onto a fast photodetector. The generated RF beat note was then sent to an electrical spectrum analyser in order to establish the full width at half maximum (FWHM) linewidth of the convolved signal. A sweep time of 25 μs was used and as shown in Figure 3, a Voigt fit was used to establish that the shape of the peak was correct. The resulting linewidth was 612 kHz which is below the 1 MHz target for cooling in cold atom systems.

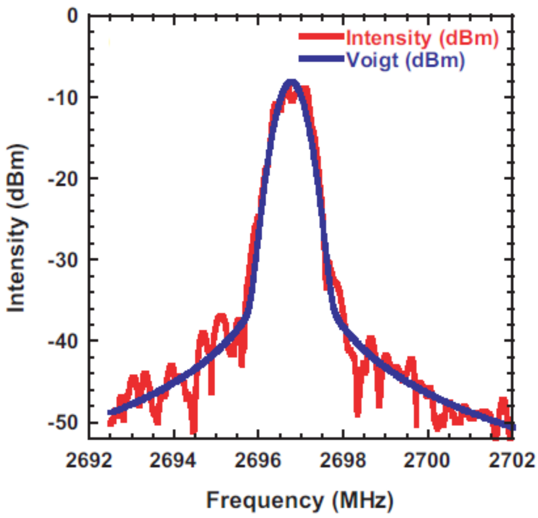

Figure 3 Linewidth measurement showing the beat note and Voigt fit resulting in a linewidth of 612 kHz.

Similar characterisation was carried out on the GaN DFBs, with a typical LIV characteristic shown in Figure 4(a) and optical spectrum in Figure 4(b). This device has a similar threshold value of approximately 140 mA, however exhibits a much higher voltage. This laser produces approximately 17 mW of power at 250 mA, however similar devices have shown over 30 mW, with a side-mode suppression ratio of over 35 dB.

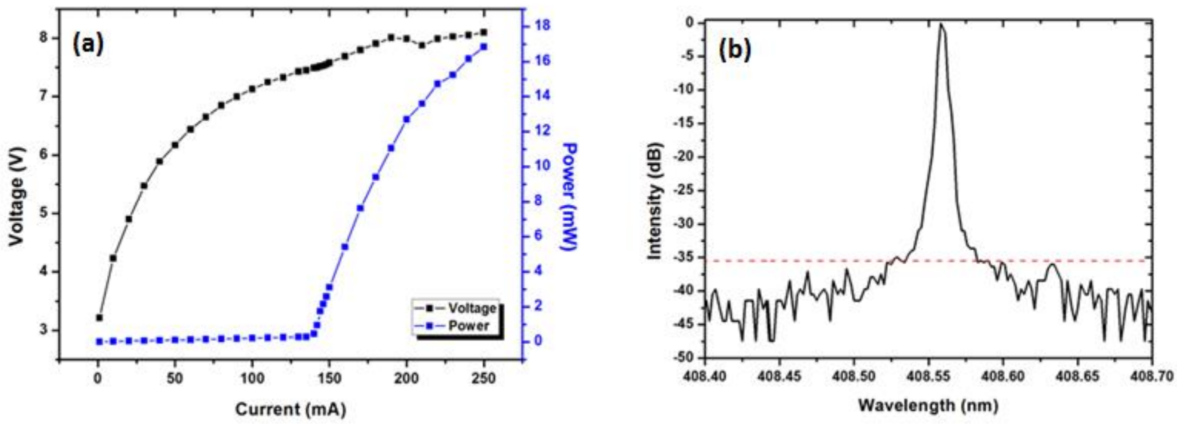

Figure 4(a) LIV and (b) spectral performance for a GaN DFB laser.

Again, the linewidth of the laser was measured, this time using a different technique to that mentioned above. A scanning Fabry-Perot interferometer can be used to measure the linewidth of some lasers, however is limited to a resolution of approximately 6 MHz, and hence would not be useful for the narrow linewidth lasers mentioned earlier at 780 nm. However, narrow linewidth GaN DFB lasers are a relatively modern concept and the linewidth values are still being optimised. Using this technique, a linewidth of 18.7 MHz was achieved on a DFB laser emitting around 421 nm. As seen in Figure 5(b), the result was verified by varying the power and observing the change in linewidth. This result follows the expected inverse relationship of laser linewidth with optical power.

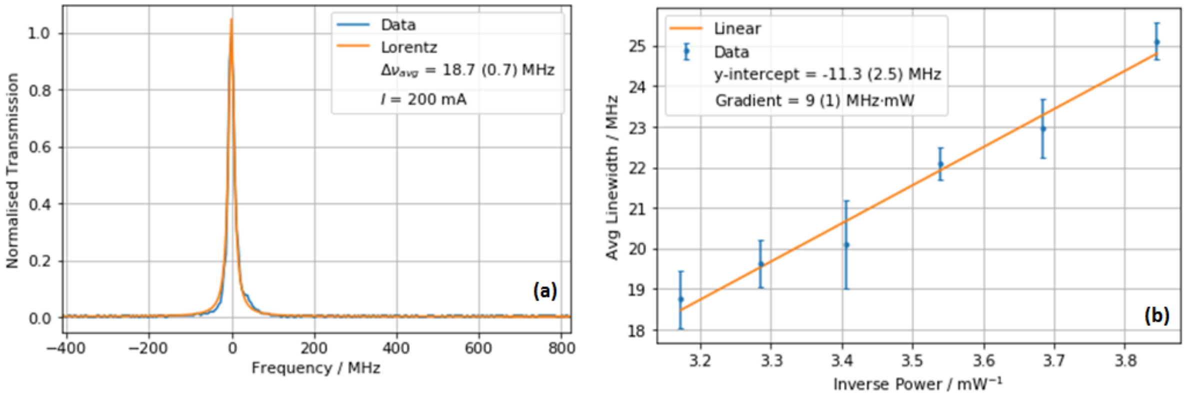

Figure 5(a) Linewidth results using the Fabry-Perot interferometer technique on a GaN DFB laser.

4. CONCLUSION

In summary, DFB lasers have been demonstrated at two key wavelengths of 780.24 nm and 422 nm for use in the cooling process in atomic clocks. The design and fabrication of the devices was outlined, optimising the devices in terms of peak wavelength, output power, threshold and linewidth. A device emitting at 780.24 nm produced output powers in excess of 60 mW with a side-mode suppression ratio of over 40 dB, with the GaN counterpart producing approximately 20 mW of power. Narrow linewidths have been achieved using both devices with a linewidth of 612 kHz achieved at 780.24 nm and 18.7 MHz achieved at 422 nm, making these devices ideal candidates for atomic clock applications.

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