Atomic Fluorescence Coupled into an Optical Nanofibre: Theory

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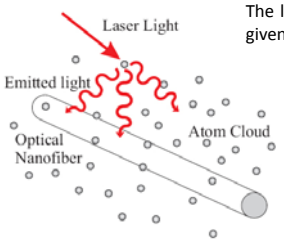
1. Introduction

Optical nanofibres have become a research focus for several groups worldwide during the past couple of years due to their attraction as tools for trapping and manipulating cold atom clouds. Consideration of the van der Waals (vdW) and Casimir-Polder (C-P) forces that arise when atoms are in the vicinity of the nanofibre lead to (i) a modification of the spontaneous emission rate from the atoms located near the nanofibre surface and (ii) a modification to the coupling efficiency of the atomic fluorescence into the nanofibre. We examine the efficiency of coupling and describe the asymmetry of the lineshape caused by the red-shift due to the vdW and C-P interactions of the atoms with the surface of an optical nanofibre.

2. Fluorescence Coupling

An ensemble of 2-level atoms, normally distributed around a nanofibre, are irradiated with near-resonant laser light. The resultant emissions couple into the fundamental guided mode of the fibre via the evanescent field.



The light power coupled into the fundamental mode is given by:

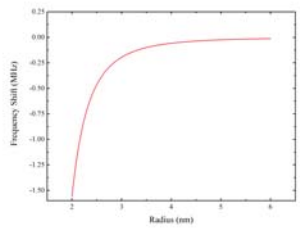
$$P = \hbar\omega \int \frac{\gamma^{(g)}(r)\Omega^2}{\left[\omega - (\omega_0^0 + \delta\omega(r))\right]^2 + \gamma^2(r)} n(\mathbf{r}) dV$$

This term, $\omega_0(r)$, has contributions from both the *van der Waals* and *Casimir-Polder* interactions.

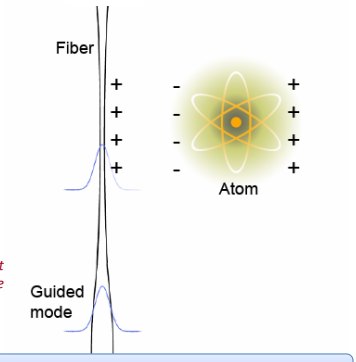
3. Van der Waals Interaction

The dipole transition frequency is shifted due to temporary dipoles set up by moving electrons in the nanofibre and atom cloud. It is dominant near the fibre surface.

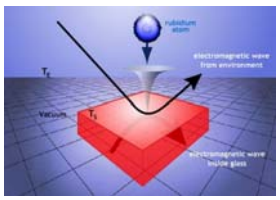
$$\delta\omega_{vdW}(r) = \frac{C_{3g}}{(r-a)^3} \quad for\ a < r < a + \lambda/10$$



Plot of shift in ω_0 due to the van der Waals effect for the range of 200 nm to 600 nm from the fibre central axis. The vertical scale is in MHz.



4. Casimir-Polder Interaction



The C-P force is an attractive QED force between an atom and a surface. Whereas the vdW effect is a microscopic one which occurs over short distances, the C-P effect is macroscopic and occurs over longer distances.

It has been shown that hotter surfaces display enhanced attractive C-P force.†

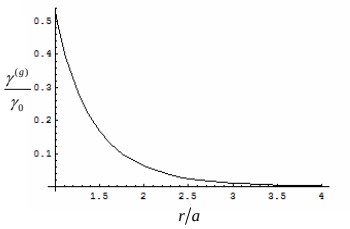
The presence of the C-P effect for atom-fibre separations of ≈$a+\lambda/10$ modifies the fluorescence spectrum according to:

$$\delta\omega_{CP}(r) = \frac{3\gamma_0}{8\pi}\frac{\varepsilon - 1}{\varepsilon + 1}\left(\frac{\lambda}{2\pi(r-a)}\right)^4 \varphi(\varepsilon) \quad for\ a + \lambda/10 < r < \infty$$

† J. M. Obrecht, R. J. Wild, M. Antezza, L. P. Pitaevskii, S. Stringari, E. A. Cornell, PRL **98**, 063201 (2007).

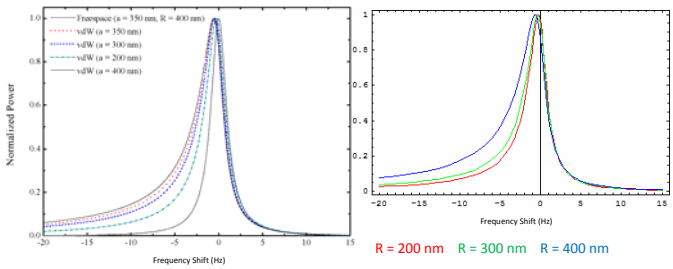
5. Results

For atoms near the fibre surface, the spontaneous emission rate into the guided mode increases dramatically. As expected, the closer the atoms are to the fibre, the more light is coupled into it.



Normalized spontaneous decay rate of 2-level atom into the fundamental guided mode as a function of distance between the atom and the axis of the optical nanofibre.

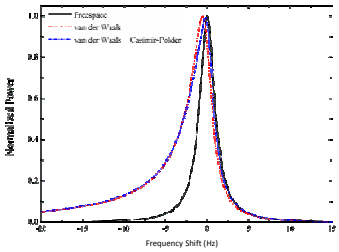
By including the vdW effect in the power equation, we observe a red-shift in the spectrum *w.r.t.* the free-space line shape. Here, we use ^{133}Cs atoms. Calculations have also been performed for ^{85}Rb but show no qualitative difference.



Effect of the vdW shift on the power spectrum for varying fibre radius. As $a \to R$, more atoms 'see' the vdW potential, leading to larger red-shift and broadening.

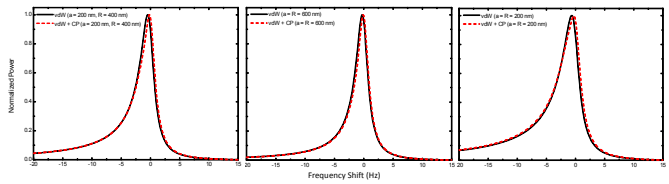
By varying R for fixed fibre radius a, we see the red-shift increasing as $R \to a$.

By including both the vdW and C-P effects into the power equation we observe similar effects. The combined vdW and C-P interaction red-shift the spectrum slghtly less than the vdW does on its own.



Power spectrum for different shift contribution. The fibre radius is 350 nm and the cloud radius is 400 nm.

The C-P effect induces negligible additional broadening when considered in conjunction with vdW as well as a reduction in frequency shift. This is present for large and small atom clouds.



Our nanofibres are created from single mode optical fibre using a 'heat + pull' technique. The transmission is monitored while two motors stretch the fibre over an oxy-butane flame. (For experimental method, see Poster: A. Watkins, "Light transmission through a tapered optical fibre.")

6. Conclusions & Outlook

We analysed the spectrum produced by excited 2-level atoms fluorescing near a nanofibre surface. The spectrum has a prominent red-shift due to atom-surface interactions. For a complete treatment, we see that it is necessary to consider both the vdW and C-P interactions. Although the change in broadening due to the inclusion of the C-P interaction is negligible, a change in red-shift is evident. The spontaneous emission rate is also modified to reflect large emission rates near the fibre surface. In future work, the cylindrical geometry of the nanofibre will be considered.

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