Optical frequency generation using fiber Bragg grating filters for applications in portable quantum sensing: supplement

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1. GENERATING MULTIPLE OPTICAL FREQUENCIES

Both laser cooling and Raman excitation require two optical frequencies to be generated simultaneously. When these are generated in a single, frequency-doubled laser beam, the process is subject to sum frequency generation. For a laser beam with frequencies, $\Omega_1$ and $\Omega_2$, with electric field amplitudes, $E_1$ and $E_2$, the electric field strength can be described as:

$$E(t) = E_1 e^{-i\Omega_1 t} + E_2 e^{-i\Omega_2 t} + \text{c.c.}.$$  \hfill (S1)

When this is incident on a nonlinear crystal with a second-order electric susceptibility, $\chi^{(2)}$, a nonlinear polarization is created:

$$P^{(2)}(t) = \epsilon_0 \chi^{(2)} E(t)^2$$  \hfill (S2)

where $\epsilon_0$ is the permittivity of freespace. This can be shown to generate light at frequencies $2\Omega_1$, $2\Omega_2$, $\Omega_1 + \Omega_2$ and $\Omega_1 - \Omega_2$[1]. Assuming only two frequencies, $\Omega_A$ and $\Omega_B$, are desired at the laser output, and the desired amplitude of $\Omega_A > \Omega_B$, spectral purity is maximized by setting $\Omega_A = 2\Omega_1$ and $\Omega_B = \Omega_1 + \Omega_2$. Figure S1 shows spectra before and after the nonlinear crystal.

![Fig. S1. Optical spectra before and after the nonlinear crystal. Black and dotted lines denote frequencies reflected and transmitted by the fiber Bragg gratings respectively.](image)

For frequency sidebands at RF frequencies, $\omega_1$ and $\omega_2$, which are applied with an electro-optic modulator at 1560 nm, the optical spectrum after the nonlinear crystal will contain the desired frequencies at $\Omega_A = 2\Omega_{\text{seed}} - 2\omega_1$ and $\Omega_B = 2\Omega_{\text{seed}} - (\omega_1 + \omega_2)$, where $\Omega_{\text{seed}}$ is the optical frequency of the seed laser. Notably, the difference in frequencies, $\Delta\Omega$, is the same before and after the nonlinear crystal, i.e. $\Omega_A - \Omega_B = \Omega_1 - \Omega_2$. $\Omega_{\text{seed}}$ is locked at $\Omega_{\text{lock}} + \omega_{\text{offset}}$, where $\Omega_{\text{lock}}$ is the frequency of the atomic reference and $\omega_{\text{offset}}$ is the lock offset frequency.

During laser cooling, the cooling optical frequency is swept whilst the repumper frequency remains fixed. Because the amplitude of the repumper frequency is less than that of the cooling, the cooling and repumper frequencies are generated at $\Omega_A$ and $\Omega_B$ respectively. Because $\Omega_B$ is dependent on both $\omega_1$ and $\omega_2$, to maintain the repumper at a fixed optical frequency, $\omega_2$ must be decreased when $\omega_1$ is increased. This was achieved experimentally by generating $\omega_1$ and $\omega_2$ using RF mixers with a common intermediate frequency, as shown in Figure 3.

REFERENCES