Frequency up-conversion of microwave photons to the telecommunications band in an 
Er:YSO crystal

Xavier Fernandez-Gonzalvo,1 Yu-Hui Chen,1 Chunming Yin,2 Sven Rogge,2 and Jevon J. Longdell1

1The Dodd-Walls Centre for Photonic and Quantum Technologies & Department of Physics, University of Otago, 730 Cumberland Street, Dunedin, New Zealand.
2Centre of Excellence for Quantum Computation and Communication Technology, School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
(Dated: January 12, 2015)

The ability to convert quantum states from microwave photons to optical photons will be important for hybrid system approaches to quantum information processing. In this paper we report the conversion of microwave photons into telecommunications band photons using erbium dopants in a yttrium orthosilicate crystal using stimulated Raman scattering. The microwaves were applied to the sample using a 3D copper loop-gap resonator and the signal and coupling optical fields were single passed. The conversion efficiency was low, in agreement with a theoretical analysis, but can be significantly enhanced with an optical resonator.

PACS numbers:

Superconducting qubits are a rapidly advancing part of quantum information science. The ability to reach deep into the strong coupling regime of cavity QED using microwaves has revolutionized quantum optics in the microwave regime [1–4], and allows the coupling between superconducting qubits and a broad range of microwave frequency quantum systems [5, 6]. Distribution and storage of microwave quantum states, however, present difficult challenges. A way around this problem would be to convert quantum states of microwave photons into optical photons and vice versa. This would allow long distance propagation of quantum states between superconducting qubit nodes using optical fibres, and it would also allow for quantum memories for light to be used [7–11], which are currently more developed than their microwave counterparts [12–15]. Quantum frequency conversion has been achieved between optical frequencies [16–20], and recently between microwave frequencies [21]. However, so far, quantum frequency conversion from the microwave to the optical domain remains an unsolved challenge.

There are a number of approaches being investigated for the up-conversion process. Opto-mechanical approaches [22–26] currently have the highest reported efficiencies. In such approaches both an optical and a microwave resonators are parametrically coupled through a micro-mechanical resonator. In order to have quiet frequency conversion this rather low frequency intermediate mechanical resonator needs to be cooled to its quantum ground state, and this is currently challenging. Another approach is to use conventional non-linear optical materials to make resonantly enhanced modulators [27–29].

Two recent proposals [30, 31] have suggested using rare earth doped solids, with a particular focus on erbium doped yttrium orthosilicate (Er:YSO). Er:YSO has many attractive features for frequency up-conversion: it has narrow inhomogeneous and homogeneous linewidths for its $^4I_{15/2} \leftrightarrow ^4I_{13/2}$ optical transition [32], and the wavelength of this transition is in the telecommunications band, where propagation losses in optical fibres are minimized. Because Er$^{3+}$ is a Kramer’s ion (odd number of $4f$ electrons), for the nuclear spin free isotopes (all but $^{167}$Er), the ground state is doubly degenerate. It also has rather large effective $g$ values [33, 34], such that microwave frequency splittings can be achieved with only modest magnetic fields.

In the present letter we report up-conversion of microwave to optical photons using rare earth ion dopants.

---

FIG. 1: (Color online) Left: the Raman heterodyne signal is produced when a microwave field $\Omega_\mu$ and an optical field $\Omega_\xi$ drive three levels in an atom. A coherence is produced on the third transition which generates an optical signal field $\Omega_S$. This signal field is then detected as a beat note on the optical drive field, i.e. a modulation in the optical output power $P_\text{out}$ at the same frequency as the microwave field. Right: depiction of the experimental setup. A copper made loop-gap resonator holds an Er:YSO sample inside. Optical light is coupled in and out using a pair of prisms and fibre coupled collimators. Microwave input and output of the cavity is performed via a couple of straight antennas. The magnetic field $\mathbf{B}$ goes in the vertical direction, parallel to the $D_1$-$D_2$ plane of the crystal, at an angle $\alpha$ as measured from $D_1$. 

arXiv:1501.02014v1 [quant-ph] 9 Jan 2015
in a crystal, by performing microwave Raman heterodyne spectroscopy [35] in Er:YSO. Raman heterodyne spectroscopy with radio frequency (ca. 0-200 MHz) is a commonly used technique for nuclear spins in rare earth dopants. It has also been demonstrated in the microwave regime in ruby [36, 37] and metalloproteins [38]. These systems, however, are not as attractive for the realization of quantum frequency conversion because they exhibit much broader optical lines.

Raman heterodyne spectroscopy uses the three wave mixing that occurs from three energy levels in a $\Delta$ configuration, as shown in Fig. 1. To enhance the efficiency of the process we use a microwave resonator for the lowest frequency field. The $^{4}I_{15/2}$ ground state of Er:YSO is Zeeman split under the presence of an applied magnetic field $\vec{B}$ until the $|1\rangle \leftrightarrow |2\rangle$ transition resonates with the microwave cavity. Then, when the input microwave field $\Omega_{m}$ is applied it generates a coherence between levels $|1\rangle$ and $|2\rangle$. Simultaneously, the optical coupling field $\Omega_{s}$ drives a second coherence between levels $|2\rangle$ and $|3\rangle$. The presence of these two coherences generates a third one between levels $|1\rangle$ and $|3\rangle$, which gives an output signal field $\Omega_{s}$ at a frequency equal to the sum of the frequencies of the microwave and the coupling fields. As long as the sample is small compared to the wavelength of the microwave field the signal field will be generated in the same spatial mode as the coupling beam. The signal optical field can then be easily detected in a photodiode as a heterodyne beat note on the coupling beam.

The crystalline structure of YSO belongs to the $C_{2h}^{6}$ symmetry group, with two crystallographically inequivalent sites where erbium can replace yttrium. In this work we focused on ‘Site 1’ with a transition wavelength of $\lambda_{1} = 1536.478$ nm [39]. YSO has three orthogonal optical extinction axes $D_{1}$, $D_{2}$ and $b$.

A representation of the experimental configuration is also shown in figure 1. We use a cylindrical Er:YSO sample of 4.95 mm diameter by 12 mm length, with an erbium number concentration of 0.001%. The optical $b$ axis of the crystal is aligned along the length of the cylinder, and so the $D_{1}$-$D_{2}$ plane is parallel to the end faces. The sample sits inside a copper three-dimensional loop-gap microwave resonator, with a resonant frequency of 4.9 GHz and a linewidth of 16 MHz (quality factor $Q \approx 300$). Input and output microwave powers are coupled with a pair of straight antennas inside the cavity space. Two holes on the caps of the resonator allow for optical access. The input light comes from a fibre coupled tunable external cavity diode laser at 1536 nm. It is coupled into and out of the sample with the aid of a pair of coupling prisms, and GRIN-lens fibre coupled collimators. The input fibre is a single mode fibre, while for the output one we use a multi-mode fibre for ease of coupling. The whole experimental ensemble is fitted into a 40 mm diameter tube filled with $\approx 1$ mbar of helium that is submerged into liquid helium in a bath cryostat. A superconducting magnet wrapped around the end of the tube, at the sample height, allows for the generation of a magnetic field perpendicular to the longitudinal direction of the sample (i.e. in the $D_{1}$-$D_{2}$ plane) between 0 and 300 mT. The angle $\alpha$ measured from $D_{1}$ to $\vec{B}$, can be varied by rotating the sample.

The transition strengths for each of the optical transitions in Fig. 1 is given by the product of the electronic transition dipole moment and the overlap of the two spin states. This overlap is calculated by diagonalizing the spin Hamiltonian [33] an taking the inner product of the respective eigenstates. The orientation of the magnetic field has to be chosen carefully, so as to maximize the difference between the quantisation axes for the ground and excited states and thus allow $\Delta$ transitions. For the situation in which $\vec{B}$ is contained in the $D_{1}$-$D_{2}$ plane the calculated angle that maximizes the overlap between states $|2\rangle$ and $|3\rangle$ is $\alpha_{M} = 29^\circ$.

The heterodyne signal detected in the photodiode will be composed of an AC and a DC parts, that are separated using a bias tee, which is also used to bias the detector. The AC component is high-pass filtered and amplified, and sent into an RF spectrum analyzer. An inconvenient consequence of using a multi-mode fibre for the output light is that there is loss in the modulation due to de-phasing of the different propagation modes. This loss was typically between a factor of 2 to 4 and depends on the arrangement of the fiber.

Our Raman heterodyne spectroscopy results are presented in the color plot of Fig. 2. The power of the generated signal field $P_{s}$ is measured as we scan the magnetic field and the coupling laser frequency $f_{c}$. On the left side, in white, we plot an optical absorption spectrum for $|\vec{B}| = 0$ (dotted line) and for $|\vec{B}| = 0.178$ T (solid line). Note that due to various etalon effects the background of these measurements is not constant. In the optical absorption spectrum for $|\vec{B}| = 0.178$ T the four optical transitions can be observed. The strong ones ($|1\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |4\rangle$) appear as peaks around $\Delta f_{c} = \pm 1.6$ GHz, while the weak ones ($|1\rangle \leftrightarrow |4\rangle$ and $|2\rangle \leftrightarrow |3\rangle$) appear as smaller shoulders at about $\Delta f_{c} = \pm 3.4$ GHz. The ratio between the absorption level of the weak and the strong lines is close to the expected value for $\alpha \approx \alpha_{M}$. From the absorption measurements we can also extract an inhomogeneous broadening of the optical transition of $\sim 2.5$ GHz FWHM. Comparing the Raman heterodyne spectroscopy data with the absorption spectrum at $|\vec{B}| = 0.178$ T we see that the main four peaks in the color plot (in red) coincide with the absorption on each of the lines, as it is to be expected. It can also be seen that the peak signal is slightly higher for the lowest frequency peaks, which can be explained using hole burning arguments.

Beneath the Raman heterodyne spectroscopy data is the electron paramagnetic resonance (EPR) spectrum of our sample. To take these measurements we applied a frequency modulated (FM) microwave signal into the input
FIG. 2: (Color online) Top: Raman heterodyne spectroscopy on Er:YSO, showing frequency conversion from microwave to telecom frequencies. The strength of the magnetic field is plotted in the horizontal axis, and the coupling laser detuning is plotted on the vertical axis. The color scale indicates the power of the output signal field. On the left the white dotted line represents the optical absorption spectrum for $|\vec{B}| = 0$. The solid white line corresponds to the optical absorption spectrum for $|\vec{B}| = 0.178$ T. Bottom: EPR spectrum of the Er:YSO sample. The regions away from the main peaks have been magnified for clarity. In both plots the presence of double peaks along the horizontal axis is due to misalignment in the magnetic field, breaking the magnetic degeneracy of the two inequivalent orientations of Er$^{+3}$ in YSO.

port of the microwave cavity and monitored the transmitted intensity using a lockin amplifier. In this way we were able monitor the resonance frequency of our cavity as is done in Pound frequency locking [40]. As the spin transitions were swept through resonance with the cavity they pulled the resonator frequency first one way then the other resulting in dispersive shaped peaks. The collection of vertical lines in the Raman heterodyne spectrum and the smaller peaks in the EPR spectrum are due to the $^{167}$Er isotope, which has non-zero nuclear spin ($I = 7/2$) and therefore exhibits hyperfine splitting even for $|\vec{B}| = 0$.

For the EPR we measurements applied a frequency modulated (FM) microwave signal into the input port of the microwave cavity and monitored the transmitted intensity using a lockin amplifier. So as is done in Pound frequency locking [41] we were able monitor the resonance frequency of our cavity. As the spin transitions were swept through resonance with the cavity the pulled the resonator frequency first one way then the other resulting in dispersive shaped peaks.

Comparing the Raman heterodyne and the EPR spectra we can see that most of the features present in the Raman heterodyne spectroscopy data are also replicated in the EPR spectrum. The EPR peak present at $B \approx 0.03$ T we assign to the Er atoms in Site 2. Because the optical transition for these atoms is at a different frequency we don’t see a signal in the Raman heterodyne spectroscopy data.

Figure 3 shows, in red, the dependence of the signal field power with the input microwave power and the detected coupling laser power $P_\xi$. The laser coupling power is measured at the output of the system, and is not corrected for optical losses between the sample and the power meter. In blue we plot the expectations for these measurements based on our theoretical model, briefly discussed below. The dependency of $P_S$ with $P_\mu$ follows the expected pattern for a three wave mixing process: it increases linearly until it reaches a saturation point, in our case around $P_\mu = -20$ dBm. These measurements are taken for a detected coupling laser power $P_\xi = 1.8$ mW.

The dependency of $P_S$ with $P_\xi$, however, doesn’t follow a linear relation for small laser powers. This is because the coupling laser pumps the population from state $|2\rangle$ into state $|1\rangle$, which means we are effectively cooling down the spins to a lower temperature with the coupling laser light. This fact is particularly convenient since, for a low noise conversion process, the spins temperature will need to be small compared with the frequency of the input microwave field. These measurements are taken for an input microwave power $P_\mu = 0$ dBm.

To model the experiment and plot the blue lines in Fig. 3, we treated each erbium atom as a three level system and used standard master equation techniques. This
Erbium dopants in isotopically pure yttrium lithium fluoride [42]. Astonishingly narrow absorption lines observed in Er:YSO without the penalty of broader inhomogeneous lines [43]. The Q-factor of ~300 for our microwave resonator was also rather modest – much higher Q-factors for copper resonators have been reported [44].

In summary, we have presented a novel way to convert microwave photons into the telecommunications band, by means of a cryogenically cooled rare earth sample inside a three-dimensional microwave cavity. We have matched our Raman heterodyne spectroscopy experimental results with a theoretical counterpart. Finally, although the efficiency of this initial demonstration is low, there are many ways to improve it, the most significant of which is enhance the effect of the two optical fields with an optical resonator. Among possible designs for this optical resonator is the Fabry-Perot resonator as proposed in [30] or a whispering gallery mode type resonators as investigated in [28].

We would like to acknowledge the Marsden Fund (Contract No. UOO1221) of the Royal Society of New Zealand and the ARC Centre of Excellence for Quantum Computation and Communication Technology (CE110001027) for their support. S.R. acknowledges a Future Fellowship (FT100100589).

is described in detail in the supplementary information. The optical and spin dephasing times were not know precisely and were allowed to vary, as was the spin lifetime. In the fitting process we also introduced two free parameters $\zeta_\mu$ and $\zeta_\xi^{-1}$ which take into account the propagation losses of $P_\mu$ from the setup input to the microwave cavity and the inverse loss of $P_\xi$ from the photodiode detector to the sample. The fitted values for these loss and inverse loss parameters are $\zeta_\mu = 14$ dB and $\zeta_\xi^{-1} = 4$, which are well within the experimental expectations.

By comparing the input and the signal field powers we can calculate a number conversion efficiency $\eta_n = \frac{P_\mu f_\xi \lambda_\xi}{\lambda_\mu} e^{-\zeta_\mu}$, where $f_\mu$ and $\lambda_\mu$ are the input microwave frequency and the output signal field wavelength respectively. This efficiency $\eta_n$ accounts for the fraction of microwave photons converted into telecom photons. For a coupling power of ~2 mW and making the appropriate corrections for $\zeta_\mu$ and $\zeta_\xi^{-1}$ we get a conversion efficiency of $O(10^{-12})$. In order to get closer to the target of conversion efficiency equal to 1 the most important improvement will be to add a doubly resonant optical cavity (for the coupling and signal fields), which will improve the efficiency by a factor proportional to the finesse of the cavity squared $F^2$, where $F$ can be as high as $O(10^5)$. On top of this effect, cavity enhancement of the coupling field should increase the effectiveness of the optical cooling of the spins, additionally increasing the efficiency of the conversion process. There are also numerous other improvements that can be made. A more homogeneous magnetic field is very desirable, since it would reduce the microwave inhomogeneous linewidth.

The optical depth used in this experiment was also rather low (0.02 mm$^{-1}$). Much larger optical depths have been observed in Er:YSO without the penalty of broader inhomogeneous lines [42].

\begin{thebibliography}{9}

[1] Y. Kubo, F. R. Ong, P. Bertet, D. Vion, V. Jacques, D. Zheng, a. Dréau, J.-F. Roch, a. Auffret, F. Jelezko, et al., Physical Review Letters 105, 140502 (2010), ISSN 0031-9007, URL http://link.aps.org/doi/10.1103/PhysRevLett.105.140502.

[2] D. I. Schuster, a. P. Sears, E. Ginossar, L. DiCarlo, L. Frunzio, J. J. L. Morton, H. Wu, G. a. D. Briggs, B. B. Buckley, D. D. Awschalom, et al., Physical Review Letters 105, 140501 (2010), ISSN 0031-9007, URL http://link.aps.org/doi/10.1103/PhysRevLett.105.140501.

[3] J. D. Teufel, D. Li, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, and R. W. Simmonds, Nature 471, 204 (2011), ISSN 0028-0836, URL http://dx.doi.org/10.1038/nature09898.

[4] S. Probst, H. Rotzinger, S. Wünsch, P. Jung, M. Jerger, M. Siegel, a. Ustinov, and P. Bushev, Physical Review Letters 110, 157001 (2013), ISSN 0031-9007, URL http://link.aps.org/doi/10.1103/PhysRevLett.110.157001.

[5] M. D. LaHaye, J. Suh, P. M. Echternach, K. C. Schwab, and M. L. Roukes, Nature 459, 960 (2009), ISSN 0028-0836, URL http://dx.doi.org/10.1038/ nature08093http://www.nature.com/nature/journal/v459/n7249/suppinfo/nature08093_S1.html.

[6] X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S.-i. Karimoto, H. Nakano, W. J. Munro, Y. Tokura, M. S. Everitt, K. Nemoto, et al., Nature 478, 221 (2011), ISSN 0028-0836, URL http://dx.doi.org/10.1038/nature10462http://www.nature.com/nature/journal/v478/n7368/abs/nature10462.html#supplementary-information.

[7] J. J. Longdell, E. Fraval, M. J. Sellars, and N. B. Manson, Physical Review Letters 95, 063601 (2005), ISSN 0031-9007, URL http://link.aps.org/doi/10.
[43] E. Chukalina, M. Popova, S. Korabieva, and R. Abdulsabirov, Physics Letters A 269, 348 (2000), ISSN 0375-9601, URL http://www.sciencedirect.com/science/article/pii/S0375960100002735.

[44] S. Probst, A. Tkaličec, H. Rotzinger, D. Rieger, J.-M. Le Floch, M. Goryachev, M. E. Tobar, A. V. Ustinov, and P. A. Bushev, Phys. Rev. B 90, 100404 (2014), URL http://link.aps.org/doi/10.1103/PhysRevB.90.100404.