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Arbitrary unitary transformations on optical states using a quantum memory

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Abstract. We show that optical memories arranged along an optical path can perform arbitrary unitary transformations on frequency domain optical states. The protocol offers favourable scaling and can be used with any quantum memory that uses an off-resonant Raman transition to reversibly transfer optical information to an atomic spin coherence.

Keywords: Quantum optics, quantum information, optical quantum memory
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Optical quantum networks will require active and passive linear optics to process quantum information in a manner that does not disrupt the quantum state of the light. Additionally, quantum memories that are capable of storing optical states and subsequently recalling them with minimal loss or degradation will be required for synchronisation and feed-forward [1, 2, 3]. These requirements have driven significant research into the development of integrated linear optical networks [4] as well as efficient and noiseless optical quantum memories [5, 6, 7].

Here, we propose integrating linear operations on frequency-domain optical states into a Raman-transition based quantum memory. We show that a set of optical memories can behave as a dynamically configurable linear optical network and could be used to perform any unitary operation with high fidelity and efficiency.

Our protocol relies on the reversible mapping of an arbitrary superposition of frequency-multiplexed optical states to a collective spin excitation via a far-off-resonant Raman transition. The mechanism by which this mapping is accomplished is not crucial to the protocol. We choose to focus on the gradient echo memory protocol because it has demonstrated the efficient storage and recall of quantum states [5, 8].

We consider a three-level atomic ensemble, shown in figure 1 (a), driven by a set of bright control fields with Rabi frequencies Ω_n each at a detuning Δ_n and weak probe modes $\hat{\mathcal{E}}_n$, each of which is in two-photon resonance with a corresponding control field. The atomic structure consists of a ground state, $|g\rangle$, a meta-stable state, $|s\rangle$, and an excited state, $|e\rangle$, which is coupled to $|g\rangle$ via $\{\hat{\mathcal{E}}_n\}$ and to $|s\rangle$ via $\{\Omega_n\}$. Working from the equations of motion for the system [9], it can be shown that a superposition of the probe modes is coupled to the atomic spin coherence. The particular superposition, $\hat{\mathcal{E}}'_N$, that is coupled can be selected by the control field amplitudes [10]:

$$\hat{\mathcal{E}}'_N \equiv \frac{1}{\tilde{\Omega}} \sum_{n=1}^N \frac{\Omega_n^*}{\Delta_n} \hat{\mathcal{E}}_n, \quad (1)$$

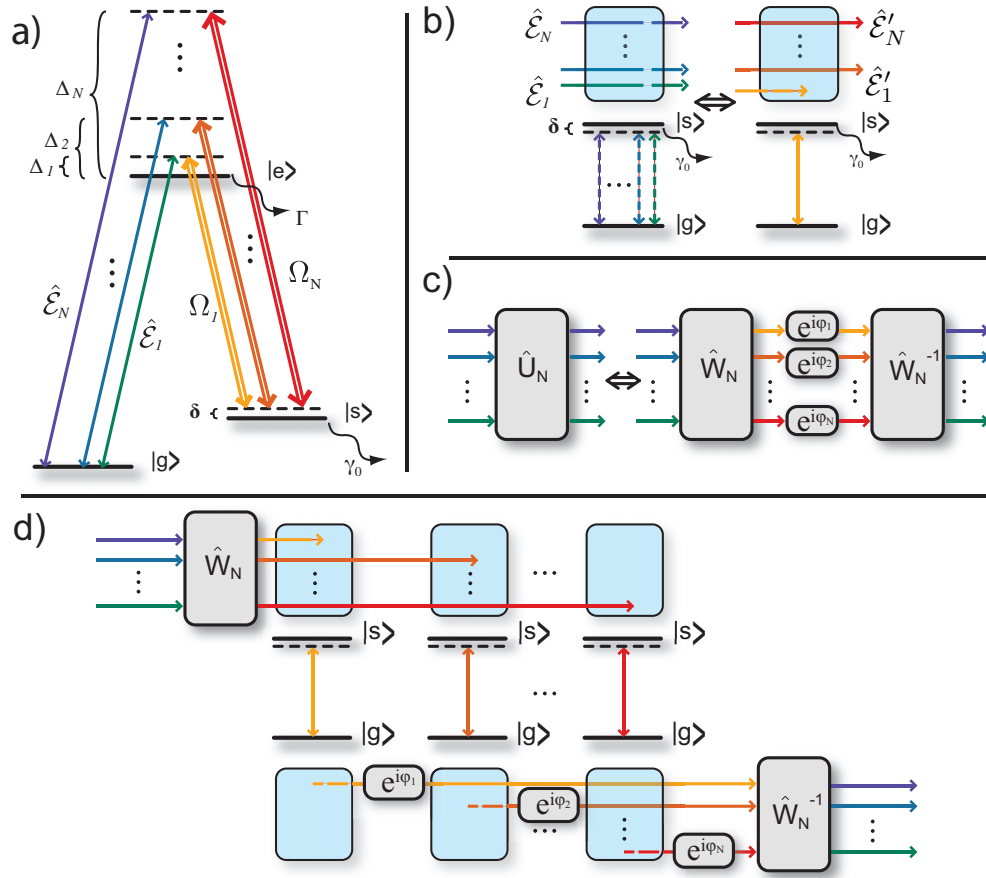


FIGURE 1. (a) Level diagram of the three-level atomic scheme. (b) Adiabatic elimination of the excited state and a basis transformation reveals that a single mode consisting of a superposition of probe fields is coupled to the atomic ensemble. (c) Any unitary transformation can be implemented by applying a phase shift to each eigenvector of the operator. Here, \hat{W}_N represents a basis transformation but does not correspond to a physical process. (d) To implement a given unitary transformation with a set of memories, each eigenvector of the operator is stored in a separate memory by selecting appropriate coupling field amplitudes. On recall, a phase shift is given to each eigenmode of the operator according to the corresponding eigenvalue.

with $\tilde{\Omega} = \sqrt{\sum_{n=1}^N |\frac{\Omega_n}{\Delta_n}|^2}$. The rest of the probe light, that which does not project onto $\hat{\mathcal{E}}'_N$, propagates through the memory unimpeded.

This treatment is valid provided that two conditions on $\delta_{m,n} \equiv |\Delta_m - \Delta_n|$ are satisfied for all pairs of modes $n \neq m$: $\delta_{m,n} \gg \frac{\Omega_m^* \Omega_n}{\Delta_m}$ and $\delta_{m,n} \gg \gamma' + \delta'$. Here, γ' is the dephasing rate of $|s\rangle$ adjusted for power broadening and δ' is the two-photon detuning adjusted for the ac-Stark shift.

The coupling of a superposition of the optical modes to the atomic ensemble can be considered a single-mode operation in a transformed basis. Working in a transformed

basis $\hat{\mathcal{E}}'$, which is any orthonormal basis that includes $\hat{\mathcal{E}}'_N$ as defined in eq. 1, one mode can be stored in the ensemble while the rest are left as optical modes (fig. 1 b).

We can implement an arbitrary unitary transformation by employing N memories, each acting on a superposition that is defined by an eigenvector of the unitary which is to be performed. Each eigenvector can be stored and subsequently recalled with an arbitrary phase shift simply by changing the phase of the control fields between storage and recall, as illustrated in fig. 1 (c), (d).

The scheme scales favourably with an increasing number of modes. The memories in our scheme are placed one after another along a single spatial mode and operate simultaneously. The operation is inherently interferometrically stable and takes only as long as one write/read operation. Loss due to memory efficiency is incurred only once for each mode and resulting in an overall efficiency that is also independent of the number of modes. The number of coupling fields scales quadratically with N ; however, if the coupling fields are generated by electro-optic modulators, additional coupling fields may be added to each memory simply by adding additional driving radio-frequency signals. The number of physical components required therefore scales linearly with the number of modes.

The protocol was simulated by numerically modelling [11] a gradient echo memory with experimental parameters. The simulation was run for 25 modes and with 40 different random unitary operations and input states. The efficiency was found to be $(68.9 \pm 0.4)\%$ with an overlap between the simulated and ideal outputs of (0.993 ± 0.002) compared to an efficiency of 72.4% for the storage of a single mode. The modes were equally separated by 5 MHz, each with a bandwidth of 300 kHz. Experimental work has also previously demonstrated the underlying interference mechanism in the context of electromagnetically induced transparency [12] and gradient echo memory [13].

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