Demonstration of a Single-Photon Router in the Microwave Regime

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We have embedded an artificial atom, a superconducting transmon qubit, in an open transmission line and investigated the strong scattering of incident microwave photons (∼6 GHz). When an input coherent state, with an average photon number $N < 1$ is on resonance with the artificial atom, we observe extinction of up to 99.6% in the forward propagating field. We use two-tone spectroscopy to study scattering from excited states and we observe electromagnetically induced transparency (EIT). We then use EIT to make a single-photon router, where we can control to what output port an incoming signal is delivered. The maximum on-off ratio is around 99% with a rise and fall time on the order of nanoseconds, consistent with theoretical expectations. The router can easily be extended to have multiple output ports and it can be viewed as a rudimentary quantum node, an important step towards building quantum information networks.

In recent years, quantum information science has advanced rapidly, both at the level of fundamental research and technological development. For instance, quantum cryptography systems have become commercially available [1]. These systems are examples of quantum channels, serving mainly to distribute quantum information. There is a significant effort to combine these quantum channels with quantum nodes that would offer basic processing and routing capability. The combination of these channels and nodes would create a quantum network enabling applications simply impossible today [2]. Quantum networks connecting simple quantum processing nodes are also a promising architecture for a scalable quantum computer.

In this Letter, we demonstrate an example of a rudimentary quantum node, a single-photon router. The active element of the router is a single “artificial atom”, a superconducting qubit, strongly coupled to a superconducting transmission line. Exploiting the phenomenon of electromagnetically induced transparency (EIT), we show that we can route a single-photon signal from an input port to either of two output ports with an on-off ratio of 99%. The switching time of the device is shown to be a few nanoseconds, consistent with theoretical expectations and the device parameters. The device is a nanofabricated circuit offering a clear path to scalability. For instance, it is straight forward to extend this router to select between multiple output channels.

An obvious requirement of a quantum channel is the ability to coherently distribute quantum information over relatively large distances. This typically implies the use of photons as information carriers, as opposed to other quantum systems such as atoms. This presents a problem when trying to implement a quantum node, as the interaction of photons with themselves is vanishingly small. Without interactions, photons cannot be controlled or directed. We can however look to control the photons by using matter as an intermediary [3–5], exploiting the strong interactions of electrons for instance. Still, the coupling of single-photon signals to bulk nonlinear materials is too weak for efficient control. A number of authors [6–9] have suggested that this problem could be overcome by resonantly coupling the signals to single atoms, which are highly nonlinear systems. While impressive technical achievements have been demonstrated in experiment, the coupling of single atoms to light remains relatively inefficient. For instance, in the prototypical experiment of scattering light from a single atom, the reduction in the intensity (extinction) of the incident light does not exceed 12% [10–13]. However, it was recently demonstrated that microwave photons can be coupled extremely efficiently to a single artificial atom, showing extinction efficiencies in an open transmission line greater than 90% [14,15]. Here we demonstrate an extinction of 99.6%, an order of magnitude increase, and use this approach as the basis of our single-photon router.

Our artificial atom is a superconducting transmon [16] qubit, consisting of two Josephson junctions in a SQUID configuration with a total capacitance $C_X$. It is capacitively coupled to a 1D transmission line [see Fig. 1(a)] in a coplanar waveguide configuration. The two lowest energy states $|0\rangle$, $|1\rangle$ have a transition energy $\hbar \omega_0(\Phi) = \sqrt{8E_JE_C - E_C} \approx 7.1$ GHz where $E_J$ is the Josephson energy of the SQUID, $E_C$ is the charging energy and $\Phi$ is the external magnetic flux. This type of qubit has been extensively studied [17–20] and successfully used to, for example, perform quantum algorithms [21] as well as produce single photons [22].

The electromagnetic field in the transmission line can be described by incoming $(+)$ and outgoing $(-)$ voltage waves on the left $(L)$ and the right $(R)$, $V_{LR}$. In Fig. 1(a), the transmission coefficient $t = V_R / V_L$ and the reflection coefficient $r = V_L / V_L$ are related by the definition,
FIG. 1 (color online). Scattering from a single artificial atom. (a) A micrograph of our artificial atom, a superconducting transmon qubit embedded in a 1D open transmission line. The light regions are Al while the dark regions are the oxidized silicon substrate. We see the center conductor of the CPW in between the two ground planes and the two plates of the interdigitated capacitance of the transmon. The enlargement is a scanning-electron micrograph of the SQUID loop of the transmon, which allows us to tune its transition frequency with an external magnetic flux \( \Phi \). The junctions are formed using the standard double-angle evaporation technique. (b) Schematic of the measurement setup. A strong control pulse at \( \omega_c = \omega_{12} \) is used to route a weak microwave signal at the probe frequency \( \omega_p \). We measure the transmitted and reflected probe simultaneously in the time domain. The circulators, numbered 1–4, allow us to separate signals propagating in different directions in the lines. (c) Transmittance, \( T = |\tau|^2 \), on resonance as a function of incident power. For \( N \ll 1 \) we see extinction of the coherent probe of 90% and 99.6% for sample 1 and 2, respectively. \( N = 1 \) for a power of \(-125 \text{ dBm (~123 dBm)}\) for sample 1 (2). The symbols are data while the lines are fits based on Eq. (1). (Inset) A weak, resonant coherent state is scattered by the atom.

When the applied probe frequency \( \omega_p \) is equal to \( \omega_{01} \), the reflection coefficient is given by [14]

\[
r = \frac{-r_0}{1 + \Omega_p^2/\Gamma_0 \gamma_{10}},
\]

where the maximum reflection amplitude is \( r_0 = 1/(1 + 2\Gamma_0\gamma_{10}) \). \( \Gamma_0 \) is the relaxation rate of the atom from \( |1 \rangle \) to \( |0 \rangle \), \( \gamma_{10} = \Gamma_{10}/2 + \Gamma_\phi \) is the 0–1 decoherence rate, and \( \Gamma_\phi \) is the 0–1 pure dephasing rate. A coherent input signal (probe) will drive coherent oscillations of the atom at a Rabi frequency which is linear in the probe amplitude and can be written as [16]

\[
\Omega_p = \sqrt{2e} \frac{C_c}{h \sqrt{8E_c}} \sqrt{PZ_0}.
\]

where \( P = |V_p^2|/2Z_0 \) is the probe power, \( Z_0 \approx 50 \text{ } \Omega \) is the impedance of the transmission line and \( C_c \) is the coupling capacitance between the qubit and the transmission line [Fig. 1(b)]. For a weak resonant probe (\( \Omega_p \ll \Gamma_{10}, \gamma_{10} \)) and in the absence of both pure dephasing (\( \Gamma_\phi = 0 \)) and unknown loss channels, such as relaxation of the qubit not associated with the coupling to the transmission line, we expect to see full reflection of the incoming probe [7,8,23]. This perfect reflection can be understood as the coherent interference between the incoming wave and the wave scattered from the atom.

We have measured the reflection and transmission coefficients in two different samples as a function of incident probe power using homodyne detection (See Supplemental Material [24]). By fitting the frequency and power dependence of this data, we extract the parameters shown in Table I.

In Fig. 1(c), we plot the transmittance \( T = |\tau|^2 \) on resonance as a function of \( P \). We can define an average number of photons per interaction time \( 2\pi/\Gamma_{10} \) as \( N \equiv 2\pi P/\hbar \omega_p \Gamma_{10} \). For \( N \ll 1 \), we see an extinction of propagating photons of up to 99% for sample 1 and 99.6% for sample 2. The strong saturation of the extinction already at single-photon powers is an indication that the scattering is caused by a single atom, since the atom can only absorb and emit one photon at a time. The reflected power (not shown) also varies with power as expected.

So far, we have considered only the lowest two energy levels of our artificial atom. In reality, the transmon has several higher states, in particular, it has a second excited state with the 1–2 transition frequency \( \omega_{12} \). This second transition can be directly measured using two-tone spectroscopy, as is illustrated in Fig. 2(a) for sample 1. We extract \( \omega_{12}/2\pi = 6.38 \text{ GHz} \), giving an anharmonicity of \( \alpha = 720 \text{ MHz} \) between the two transitions. The linewidth of the 1–2 transition is dominated by the charge dispersion of [2]. Further increasing the pump power, we observe the well-known Mollow triplet [14,25,26] (not shown). The Rabi splitting of the triplet was used to calibrate the applied microwave power at the atom.

By pumping the system at \( \omega_c = \omega_{12} \), we can observe the phenomenon of electromagnetically induced transparency (EIT)[15,27–29] based on the Autler-Townes splitting [30,31]. With the pump off, we have seen that an incident, low-power probe at \( \omega_{01} \) is reflected. For large control powers, however, the original line splits into a doublet with a separation of \( \Omega_c \) [see Fig. 2(b)], and the atom becomes transparent to the probe beam at \( \omega_{01} \).

We exploit EIT to create a single-photon router. The operation principle is explained as follows [see Fig. 2(c)].

<table>
<thead>
<tr>
<th>Sample</th>
<th>( E_f/h )</th>
<th>( E_c/h )</th>
<th>( \Gamma_{10}/2\pi )</th>
<th>( \Gamma_\phi/2\pi )</th>
<th>Ext.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.7</td>
<td>0.59</td>
<td>0.073</td>
<td>0.018</td>
<td>90%</td>
</tr>
<tr>
<td>2</td>
<td>21.5</td>
<td>0.35</td>
<td>0.096</td>
<td>0.002</td>
<td>99.6%</td>
</tr>
</tbody>
</table>
We input a weak, continuous probe in the single-photon regime at $\omega_{01}$. We then apply a strong control pulse, around 30 dB stronger than the probe, at $\omega_c = \omega_{12}$. When the control is on, the photons are reflected by the atom and travel through the circulator to output 1. When the control is off, the photons are transmitted due to EIT, and travel to output 2. The measurement setup is shown in Fig. 1(b), which enables us to measure the reflected and transmitted probe power simultaneously in the time domain. This is crucial to demonstrate that the extinction of the transmitted beam is due to reflection instead of loss. One could also envision making a photon router by simply detuning the 0–1 transition of the atom via magnetic flux through the SQUID loop. However, the power needed to generate a flux sufficient to detune our atom is several orders of magnitude higher [19].

The operation of the router is demonstrated in Figs. 2(e)–2(g). As expected, when the control is on, most of the signal is transmitted while little is reflected. For sample 2 (1), we achieve an on-off ratio of nearly 99% (90%) in both the reflectance and transmittance. We also characterized the time response of the router. For both devices, we saw no reduction in the on-off ratio down to the shortest pulses, which had a Gaussian full width at half maximum of 10 ns. An example is shown for sample 1 in Fig. 2(g). We see that the transmittance smoothly follows the control on the few ns time scale while maintaining the high on-off ratio.

\[
T(\Omega_c) = 1 - \frac{\Gamma_{10}}{2\gamma_{20} + \Omega_c^2}, \tag{3}
\]

where $\gamma_{20}$ is the decoherence rate of the 0–2 transition. Because of the larger dipole moment of the 1–2 transition [16], we have $\Omega_{20}(P) = \sqrt{2} \Omega_{10}(P)$. We define the coherent transmittance and reflectance as $T(\Omega_c) = |r(\Omega_c)|^2$ and $R(\Omega_c) = |\alpha(\Omega_c)|^2$.
For an n-port router, the routing efficiency to the kth port is \( \eta_k = T^{k-1}R \) for \( k \neq n \) and \( \eta_n = T^{n-1} \) for \( k = n \). For sample 2, we measure \( T \approx 99\% \) and \( R \approx 92\% \). Therefore, the efficiency of a four-port router would still exceed 90%. This could be further improved by further reducing the dephasing.

In conclusion, we have demonstrated a basic single-photon router with high speed and efficiency operating in the microwave regime. While microwave circuits are a promising technology for quantum nodes, it is clear that optical photons are advantageous for use in quantum channels. This identifies the development of an optical-microwave quantum interface as a key enabling technology for a hybrid quantum network. Early steps to this type of interface have recently been achieved by a number of groups [32,33].

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