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Microwave quantum memory on a controlled frequency comb

K.V. Petrovnin, N.S. Perminov, O.N. Sherstyukov, S.A. Moiseev

Abstract. **We consider a protocol of broadband quantum memory on a controlled frequency comb of spectral lines of ring microwave resonators connected to a common strip waveguide. A prototype of this memory is manufactured, on which the room-temperature preservation of microwave pulses with an efficiency of about 3% is demonstrated. The experimentally obtained efficiency can be enhanced to a level above 90% using modern microwave technologies and conducting experiments at helium temperatures, which opens a new way for the development of integrated microwave quantum memory.**

Keywords: *quantum informatics, microwave quantum memory, quantum efficiency, controlled frequency comb, ring resonator.*

1. Introduction

The development of highly efficient quantum memory (QM) and quantum interface is of great importance for the development of quantum information technologies [1–3]. During the last decade, impressive experimental results have been attained on this path in the optical domain [4–7]. This has stimulated active research on microwave QM on electron spins in a resonator, which is considered as one of the key elements in the development of a versatile superconducting quantum computer [8–10]. Practically significant QM should preserve a fair amount of short pulses with high efficiency [11], and also meet strict requirements for quantum processing of multiqubit states and error correction procedures [12]. For the implementation of long-lived multiqubit QM, schemes of reversible strong interaction of single-photon fields in a resonator with various information carriers [13] are considered, for example, with a system of nitrogen–vacancy centres (NV centres) in diamond [14], or rare-earth ions in inorganic crystals [15]. However, the experimental implementation of sufficiently high quantum efficiency along with a large QM information capacity and storage time remains one of the main problems.

K.V. Petrovnin Kazan Quantum Center, A.N. Tupolev Kazan National Research Technical University, ul. K. Marksa 10, 420111 Kazan, Russia; Kazan Federal University, ul. Kremlevskaya 18, 420008 Kazan, Russia;
N.S. Perminov, S.A. Moiseev Kazan Quantum Center, A.N. Tupolev Kazan National Research Technical University, ul. K. Marksa 10, 420111 Kazan, Russia; E.K. Zavoisky Physical-Technical Institute, Kazan Scientific Centre, Russian Academy of Sciences, ul. Sibirskii trakt 10/7, 420029 Kazan, Russia; e-mail: s.a.moiseev@kazanqc.org;
O.N. Sherstyukov Kazan Federal University, ul. Kremliovskaya 18, 420008 Kazan, Russia

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At the same time, considerable progress has also been made recently in the development of highly efficient composite circuits [13, 16, 17] for controlling light fields in a system of interconnected resonators [18]. Multiresonator (MR) systems of this type are successfully used as optical delay lines [19–21] integrated into optical fibre circuits. The appearance of high-Q-resonators [22–24] and the possibility for their integration into MR structures [25] make such systems interesting for the implementation of broadband optical and microwave QM [26–28], since they enable formation of a wide operating spectral range in the presence of resonators with different frequencies. The MR schemes can significantly increase the signal storage time [26–28] and QM quantum efficiency in the spectral range [29] which significantly exceeds the mode line width of individual resonators, while their high Q-factor provides an opportunity to significantly enhance the constant coupling with resonant atomic systems [30]. The latter properties make MR schemes promising for the development of QM and basic elements [2, 31, 32] of a versatile quantum computer.

The aim of this work is to study the QM scheme proposed in [26] on the basis of a controlled frequency comb of spectral lines of ring resonators connected to a common waveguide with the use of QM development approaches used in the photon echo technique [33–35]. Ring resonators are of interest due to their unidirectional communication with an external waveguide, which is convenient for integration with external devices and for controlling the propagation of light fields. We have manufactured an experimental prototype of five ring microwave resonators connected in series with a microstrip resonator and demonstrated the preservation of broadband microwave pulses at room temperature. Basing on the results obtained, we discuss below the possibilities for increasing the efficiency of the QM implemented with the use of modern technologies.

2. Physical model

The original idea of a QM multi-resonator scheme relies on the QM development approach based on the use of photon echo [33, 34, 36] and its variant utilising atomic systems with a periodic spectral structure of inhomogeneous broadening of resonant transition, which is known as the AFC-protocol [35]. In contrast to work [35], in the MR schemes studied by us [26, 27], instead of an atomic system, a system of ring mini-resonators connected in series with a common waveguide [26–28] is used. Using the well-known formalism of quantum optics [26, 37] for describing the interaction of input ($a_{\text{in}\,n}$) and output ($a_{\text{out}\,n}$) fields of modes in a waveguide with the fields b_n of modes in ring resonators, we obtain the equations:

$$[\partial_t + \mathrm{i}(\omega_0 + \Delta_n) + \gamma_n + k_n/2]b_n(t) = \sqrt{k_n}\, a_{\mathrm{in}\,n}(t)$$
$$+ \sqrt{2\gamma_n} f_n(t), \quad a_{\mathrm{in}\,n}(t) - a_{\mathrm{out}\,n}(t) = \sqrt{k_n}\, b_n(t), \tag{1}$$

where $\Delta_n = \Delta[n - (N + 1)/2]$ are the frequency detunings of resonators from the centre frequency ω_0; $n \in \{1, ..., N\}$; $k_n = k$ are the coupling constants between the resonators and waveguide; $\gamma_n = \gamma$ is the field attenuation decrement in resonators; $\sqrt{2\gamma_n} f_n(t)$ are the delta-correlated Langevin forces [28, 37] $[\langle f_n^+(t)\rangle = \langle f_n(t)\rangle = 0, \langle f_n^+(t) f_n(t')\rangle = \delta(t - t')]$, the contribution of which we neglect below, thus concentrating only on the study of quantum efficiency.

From equation (1), using the waveguide field relation $\tilde{a}_{\mathrm{in}\,n+1}(\omega) = \tilde{a}_{\mathrm{out}\,n}(\omega)\exp[\mathrm{i}(\omega_0 + \omega)(z_{n+1} - z_n)/c]$, in accordance with the approach [37], we find the output field through the transfer function (TF) $S(\nu) = \tilde{a}_{\mathrm{out}\,N}(\omega)/\tilde{a}_{\mathrm{in}\,1}(\omega)$ defined as

$$S(\omega) = \exp[\mathrm{i}(\omega_0 + \omega)(z_N - z_1)/c]$$
$$\times \prod_{n=1}^{N} \frac{-k_n/2 + \gamma_n + \mathrm{i}(\Delta_n - \omega)}{k_n/2 + \gamma_n + \mathrm{i}(\Delta_n - \omega)}, \tag{2}$$

where ω is frequency detuning measured from the centre frequency ω_0;

$$a_{\{\mathrm{in\,out}\}\,n}(t) = (2\pi)^{-1/2} \int \mathrm{d}\omega \exp[\mathrm{i}(\omega_0 + \omega)t]\, \tilde{a}_{\{\mathrm{in\,out}\}\,n}(\omega);$$

z_n are the coordinates of spatial location of resonators along the waveguide; c is the propagation velocity of microwave radiation along the strip line. For the case $N = 5$ (and for a larger number of resonators), the QM operating band is the frequency range $\omega \in [-(N - 1)\Delta/2; (N - 1)\Delta/2]$, where the spectral efficiency estimate $\eta(\omega) = |S(\omega)|^2$ is given by the expression $\eta \approx \exp(-4\pi\gamma/\Delta)$ for the optimised QM [26–30] with the selection of coupling parameter $k = \Delta/2$ (for $\gamma_n = \gamma$ and $\Delta_n = \Delta[n - (N + 1)/2]$) and the storage time $T_{\mathrm{echo}} \approx 2\pi/\Delta$. The emergence of the matching condition $k = \Delta/2$ distinguishes this QM type from the AFC-protocol on atoms continuously distributed in space [35], in which the highest quantum efficiency is only realised in the limit of an infinite increase in the constant of interaction of atoms with the field, i.e. at $k \to \infty$.

3. QM prototype on resonators

To test the feasibility of the MR QM implementation on a system of ring resonators, we have manufactured a prototype of this memory based on the use of microwave whispering-gallery mode (WGM) resonators. Figure 1 shows the implemented strip circuit containing a common waveguide connected to five WGM resonators. Dielectric resonators were made of a ferroelectric ceramic material by sintering of grinding products with a high permittivity ε (ε = 30–80; in this case, barium titanate $Ba_2Ti_9O_{20}$ which is widely used in practice [38–41] was employed). To obtain materials with various permittivities ε, impurities of strontium and other metals were added in the course of the grinding process. Dielectric resonators made of such materials have a high Q-factor (9000 at a carrier frequency of ~10 GHz of the fundamental mode TE_{011}) and good temperature properties. In this design, a strip was used as a waveguide, next to which miniresonators were located. Each resonator was designated to operate in the $E_{7|1|0}$ mode (a computer code was used to calculate the geometric parameters in the MATLAB software environment). Fine frequency tuning was conducted by means of fluoroplastic plates, which made it possible to vary frequency without a significant decrease in the Q-factor of resonators.

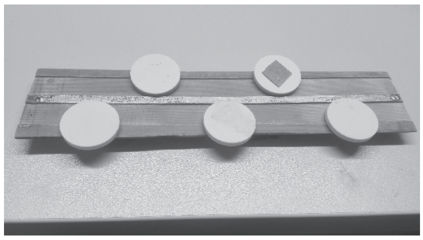

Figure 1. Prototype of a wide-band microwave MR QM on the WGM miniresonators (five resonators with different frequencies are located near a common strip waveguide; the miniresonator diameter is about 2.5 cm).

A significant difference between this system and the MR system with bulk composite resonators [28] lies in the principles of resonator operation in the whispering gallery modes and in the scheme of resonator interconnection with a common waveguide without a binding broadband buffer. Note also that the system under study is 'compressed' along one coordinate and has pseudo-planarity that provides memory compactness. The modes of the WGM resonators are excited due to their close location to the waveguide. The coupling parameter is controlled by varying the distance between the waveguide and resonator. This technology is also associated with the promising direction of developing sensitive sensors and narrow-band filters [38, 39, 42–44], where microwave WGM resonators represent a basic element [40, 41, 45, 46]. On this way we see the further development of the research on microwave QM due to the presence of open spatial geometry of the device and the possibility for its use in integration of this microwave technology with both optical and nanoscale technologies of a superconducting quantum computer [1, 17, 47].

4. Spectroscopy and echo experiment

Figure 2 shows the spectrum of memory prototype with five WGM resonators near the centre frequency ν_0 = 9.392 GHz. Preliminary experiments revealed a possibility of developing a high-quality periodic frequency comb of miniresonators from the lines being relatively narrow compared to the total spectral width of the frequency comb. The characteristic value of attenuation decrement $\gamma = \gamma/2\pi$ = 2.5 MHz was obtained for the resonator modes at a frequency spacing $\tilde{\Delta} = \Delta/2\pi$ = 10 MHz between the nearest frequencies. From the experimental data obtained, we subtracted the relatively constant level of signal losses (~50% in intensity) conditioned by the losses in the dielectric substrate of the line, and also by the defects associated with the stripline manufacture. These defects, however, can be almost completely eliminated during the factory production of the stripline or by using a dielectric waveguide. Theoretical modelling of the scheme under study (both for optical and microwave range) indicates the possibility of developing a highly efficient memory if the optimal condition ($k = \Delta/2$) for the coupling of resonators with the waveguide is fulfilled, which simplifies the implemen-

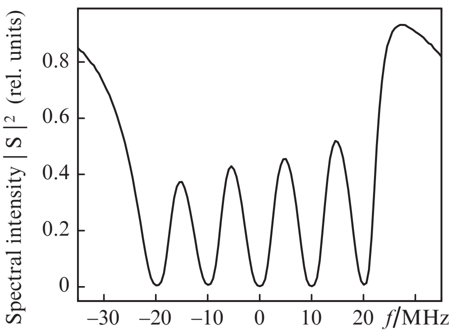

Figure 2. Frequency spectrum of the memory prototype on five WGM miniresonators connected to a strip waveguide.

tation of the scheme [26, 28, 29] at the expense of varying the coupling parameter k.

In echo-observation experiments, we attained an efficiency of about 3% for microwave pulse preservation at a pulse duration $\delta t_{\text{pulse}} = 21$ ns and $\tilde{\Delta} = 10$ MHz, which is consistent with the efficiency estimate based on the use of the solution of (2). Figure 3 shows the dependence of the normalised intensity $I(t)/I_0$ on time t, which determines the idle part of the signal transmitted without delay near $t = 0$ along the waveguide through a system of resonators, and also the echo-signal emitted with an efficiency $\eta \sim 3\%$ with the delay time $T_{\text{echo}} = 1/\tilde{\Delta} \approx 100$ ns after the idle signal. In this case, the absence in the experiment of complete matching of coupling constants and frequency detunings, leading to the appearance of an idle signal, can be eliminated by finer tuning of spectroscopic parameters of the circuit under study and by using additional resonators if a significant increase in the coupling constant is required.

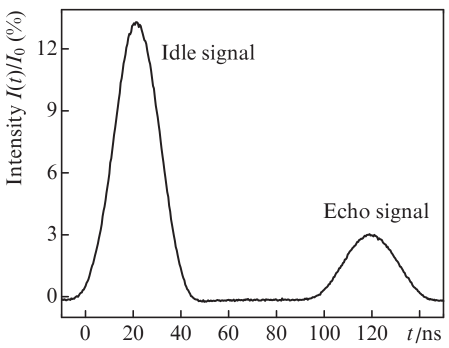

Figure 3. Normalised intensities of idle (first) and echo signals for a wideband input signal with a duration of 21 ns as a function of time.

Similar experiments were performed for other values of the frequency spacing Δ, in which the echo signal was observed with a close quantum efficiency, and its emission time also obeyed the condition $T_{\text{echo}} = 1/\tilde{\Delta}$ (Fig. 4).

When using planar superconducting technologies [38, 39, 44] and conducting experiments at low temperatures ($T \sim 10^{-2}$ K for quantum operation regime) with a Q-factor of about 10^6 ($\gamma \leqslant 10^{-3}-10^{-4}$ MHz), the efficiency value $\eta \approx \exp(-4\pi\gamma/\Delta)$ can reach 90% or more. Herewith, a significant increase in the storage time in the units of signal pulse duration is possible by increasing the number of resonators in a given MR circuit. The development of such a device will also

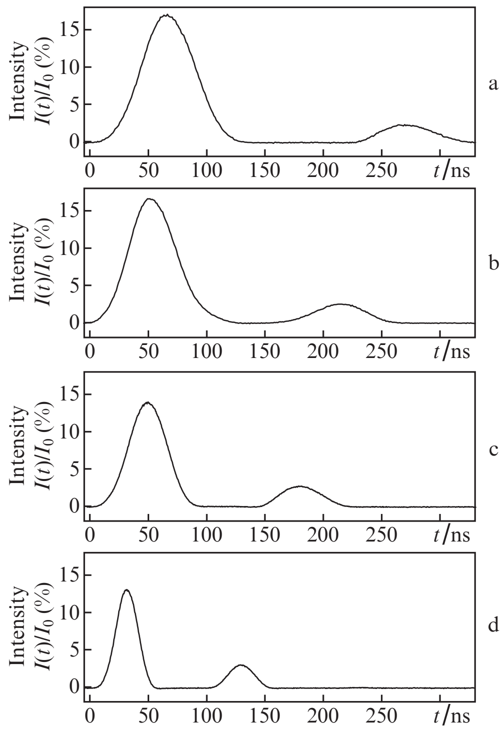

Figure 4. Intensities of the idle and echo signals for a wideband input signal as a function of time at various values of the frequency detuning $\tilde{\Delta}$, microwave pulse duration δt_{pulse}, and centre frequency ν_0: (a) $\tilde{\Delta} =$ 5 MHz, $\delta t_{\text{pulse}} = 52$ ns, $\nu_0 = 9.392$ GHz, (b) 6 MHz, 42 ns, 9.397 GHz, (c) 7.5 MHz, 36 ns, 9.402 GHz and (d) 10 MHz, 21 ns, 9.404 GHz (the signal intensity is normalised to the input signal intensity).

require the development of experimental methods for fine tuning of the MR system parameters and coupling of resonators with a common waveguide, which should be technically implemented at low operating temperatures.

The presence of a 'silence zone' between the loading of input signal into the MR system and the emergence of the echo signal indicates that the input signal energy is fully concentrated in the WGM miniresonators until the time moment $t \sim T_{\text{echo}}$ of the echo-signal emission. The latter means that there is a fundamental possibility of using the 'silence zone' for the transfer of the stored energy and information about the parameters of the conserved broadband radiation from resonators to quantum systems, for example, to electron-nuclear spin systems with a large coherence time, which will significantly increase the QM storage time in such MR systems. In this situation, the original QM multi-resonator circuit will play a role of the wideband quantum interface. It should be noted that the open geometry of the implemented circuit makes it possible to use various methods for controlling the parameters of miniresonators and methods for their coupling with a waveguide to implement a convenient connection of photon qubits with the ensembles of long-lived electron spins and to control their dynamics.

5. Conclusions

The manufactured experimental QM prototype on ring WGM miniresonators demonstrated the possibility of preservation of broadband signals with an efficiency of 3%. The presence of a 'silence zone' between the input radiation loading and the echo signal indicates the possibility of using the multi-resonator QM as a broadband quantum interface for reversible transfer of the quantum state of an input signal to the electron-nuclear spin systems for development of the long-lived composite QM. Herewith, the open geometry of the implemented circuit makes it possible to employ various methods for controlling the parameters of miniresonators and their coupling to the waveguide. The quantum efficiency value demonstrated in the present work can be improved to a level of above 90% by means of cooling the MR system to helium temperatures, which allows the Q-factor of resonators to be increased by several orders of magnitude. This opens a new way for developing an integrated microwave quantum memory based on existing superconducting technologies. Of particular interest is also the implementation of the demonstrated MR waveguide circuit in the optical frequency range in order to directly store the single-photon fields at room temperature, which is the subject of future experimental studies.

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