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6. AUTHOR(S) Marc J. Feldman		
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13. ABSTRACT (Maximum 200 words)

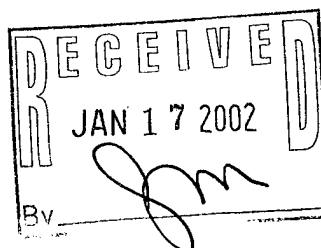
Our aim was to develop the concepts and perform the experiments to establish a clear path towards useful quantum coherent computation using superconducting flux-based qubits. We have concentrated upon using superconducting single flux quantum (SFQ) circuitry integrated on the qubit chip to act as the interface between a quantum circuit and laboratory electronics. We have developed SFQ circuits for initialization and for read-out of the quantum state of a qubit; for precise timing of durations and exact biasing, all with picosecond-scale precision. We developed a set of techniques to design such qubit control circuitry while preserving proper isolation (not significantly contributing to decoherence). We also designed an SFQ experiment to investigate quantum behavior using foundry-fabricated chips at higher temperatures. We acquired and custom set-up a He3 refrigerator, and demonstrated SFQ circuit functionality at 300 mK for the first time. We have investigated a new method for quantum control both analytically and numerically, using isolated SFQ pulses instead of resonant excitation, and shown that the minimum operation time can be dramatically decreased in some cases. However, the complete lack of custom fabrication has prevented us from making progress towards our experimental goals.

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CONTRACT/GRANT NUMBER: DAAG55-98-1-0367

REPORT TITLE: Final Progress Report for "SQUID Qubits for Quantum Computers"

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Marc J. Feldman

FINAL PROGRESS REPORT FOR THE GRANT DAAG55-98-1-0367
"SQUID QUBITS FOR QUANTUM COMPUTERS", COVERING: 6/1/98 - 5/31/01
SUBMITTED TO U.S. ARMY RESEARCH OFFICE, 12/6/01

(4) Statement of the PROBLEM studied:

Our aim in this research was to develop the concepts and perform the experiments to establish a clear path towards useful quantum coherent computation using superconducting flux-based qubits. Our first objective was to develop superconducting control and input / output circuitry as an interface to superconducting and other qubits, to bridge the classical-quantum boundary. We were to use this circuitry to demonstrate superconducting qubits with useful coherence times. This was to be done by measuring the time evolution of the Rabi-like "MQC" oscillations in a half-flux-biased rf SQUID. This would allow us to investigate the decoherence mechanisms which affected the qubits, and to do this in a controlled fashion.

(5) Summary of the most important RESULTS:

We have concentrated upon using superconducting single flux quantum (SFQ) circuitry, and in some cases RSFQ (rapid single flux quantum) digital circuits integrated on the qubit chip to act as the interface between a quantum circuit and laboratory electronics. RSFQ logic is an experimental technology which operates at clock rates of 10 to 800 GHz by transmitting and processing "bits" consisting of isolated quanta of magnetic flux, the SFQ's.

During the period covered by this grant we have made progress in the following areas: We have developed SFQ circuits for initialization and for read-out of the quantum state of a qubit; for precise timing of durations and exact biasing, all with picosecond-scale precision. We developed a set of techniques to design such qubit control circuitry while preserving proper isolation (not significantly contributing to decoherence). We designed an SFQ experiment to investigate quantum behavior using foundry-fabricated chips, and ran this experiment (without success as yet). We acquired and custom set-up a He3 refrigerator, and demonstrated SFQ circuit functionality at 300 mK for the first time. We have investigated a new method for quantum control both analytically and numerically, using isolated SFQ pulses instead of resonant excitation, and shown that the minimum operation time can be dramatically decreased in some cases. However, the complete lack of custom fabrication has prevented us from making progress towards our experimental goals.

SFQ circuits: Our work has established the benefits of using superconducting control circuitry. At the time of our proposal this seemed a radical departure, but now it is most generally agreed that superconducting control circuitry is likely to play a roll in a future solid-state quantum computer. There are three separate types of interfaces between the classical circuitry and the qubits that we have studied. The first is a dc bias, using current and/or magnetic flux as required for a particular experiment. The second is high speed electric and magnetic field coupling from waveforms on microstrip, for qubit quantum control. The third is direct coupling to RSFQ circuits for read-out and other functionality. We developed a variety of circuits to perform each of these functions:

A solid superconducting loop will hold its current, and hence the fields generated by that current, precisely constant; in our version a very large Josephson junction in the loop serves to allow the loop current to be approximately set, and then currents weakly coupled to that loop enable fine adjustment: the result being a device to generate a precisely constant magnetic field of appropriate strength with vanishing fluctuations. Our calculations indicate that the bias stability and noise immunity are easily sufficient by several orders of magnitude. In many cases it is desirable to turn on and off a small offset current very rapidly, with precisely controlled duration; in our version a superconducting loop provides this current, with allowance for the introduction and removal of an SFQ with picosecond-scale timing and precision. This small loop is weakly coupled to the larger loop, which in turn is weakly coupled to the qubits. The weak coupling allows the use of resistors in these circuits.

We developed several circuits to make classical measurements of the state of a quantum system, to read-out the quantum state, on a time scale much more rapid than the quantum evolution, the most recent circuit being similar to the quasi-one-junction SQUID used in SFQ A-to-D converters. Read-out circuits must be more strongly coupled to the qubits. We developed a strategy whereby the readout circuitry contains no resistors, and looks like a bulk superconductor during qubit evolution; the readout measurement is very rapid; the circuit needs to be reinitialized to its quiescent state after readout. This works because after readout the quantum state evolution is ended in any case.

We developed techniques for quantum control using high speed electric and magnetic field coupling from waveforms on microstrip. [Note that such quantum control is not necessary for our simplest MQC experiments.] This is done using large currents very weakly transformer coupled to the qubit. Control information can get into the qubit from the microstrip, but very little information about the state of the qubit system can get out to the external world. The information leakage goes as the square of the transformer ratio. This strategy works because the energy scale of RSFQ and other classical superconducting circuitry is hundreds to many thousands of times larger than realistic qubit energy scales. We design this using superconducting microstrip which has a much larger aspect ratio than normal microstrip. Typically it may be $10\text{ }\mu\text{m}$ wide by $0.2\text{ }\mu\text{m}$ high. This means that the fringe fields are extremely small and can be ignored, and that two microstrips have zero coupling except by design. Larger fringe fields would be detrimental for quantum computing.

We developed several on-chip superconducting (sinusoidal) oscillator designs. In addition we investigated "digital" quantum control, the use of SFQ pulses to provide a method to control quantum systems that presents an appealing alternative to the conventional methods. Rather than manipulating the state of the qubit adiabatically using relatively slow pulses close to resonant frequency of the qubit, in analogy to magnetic resonance, one subjects the qubit to a sequence of non-adiabatic picosecond-scale SFQ pulses, each with area $2.07\text{ mV}\cdot\text{ps}$. One distinct advantage is operation speed. Our calculations indicate that qubit operations can be speeded up dramatically without permanently exciting higher energy levels. We have only begun to explore SFQ pulse quantum control. So far we have only investigated regular pulse trains, but in fact arbitrary SFQ pulse sequences can be generated, with relative timing to a precision much better than a picosecond.

All of the above and many more are general-purpose circuits which are adaptable to a variety of qubit experiments. We developed a set of techniques to design these circuits while preserving proper isolation for the qubits. These are based on an intuitive and far from strictly rigorous view of decoherence, which uses the electrical engineering concepts of impedance matching and impedance transformations rather than a quantum physics calculation from a rigorous model. In our view qubit decoherence is caused by the coupling to an environment consisting of a large number of degrees of freedom, with very small coupling strength to each. In many cases such an environment may be represented as a resistor R , and it may actually be a resistor. In general however R

represents all of the dissipation coupled to the qubit, including any coupling to free space. We maintain that rigorous model calculations are inaccurate because of unrealistic assumptions which must be made to allow a tractable calculation, and in any case the final model is of limited applicability to real experimental conditions.

Fabrication: The lack of appropriate fabrication over the last several years has prevented us from making progress towards our experimental goals. Our proposal and this grant included a subcontract to Arthur Lichtenberger at the University of Virginia to fabricate the circuits we required. The Virginia laboratory was not fully capable of fabricating to our specifications (nor was any other laboratory at the time), and process modifications were required. The scope of the subcontract (\$55,000 per year) was too small to allow rapid progress on these process modifications, and it eventually became clear that we could not expect appropriate experimental chips during this grant. We then cancelled the subcontract to Virginia; ARO then took back the unspent subcontract funds from us. Although much time and effort was directed towards obtaining alternative fabrication resources, we never did have a single custom fabrication run during this entire grant.

Most superconducting circuit chips are made at the company Hypres, Inc., foundry. Hypres uses molybdenum film resistors, which go superconducting at 0.915 K. [Hypres originally told us that their resistors did not go superconducting at all, because of the state of the molybdenum, but this proved incorrect.] We did acquire a special test chip with PbPdAu resistors from Hypres and we were able to verify SFQ circuit functionality running at 300 mK., in our new He3 refrigerator, which is the first time anyone has done this.

Towards the end of this grant we established a collaboration with MIT Lincoln Laboratory for fabrication of superconducting qubit chips. One of our students spent three months at Lincoln this past Spring, to assist with the fabrication. Now we can proceed with the experimental demonstrations of our various concepts developed during this ARO grant.

ELQ experiment: We designed another SFQ experiment to investigate quantum behavior -- to demonstrate the quantization of energy levels in a Josephson junction biased near its critical current. The experiment requires that the bias current of the Josephson junction be swept more rapidly than the level population can rethermalize. This is very similar to experiments performed by other groups, with the modification that we use on-chip RSFQ circuits for all high speed functions instead of laboratory instrumentation. The great advantage for us, compared to the MQC experiment, is that standard foundry chips should be sufficient to perform this experiment, without custom fabrication. The first several times we tried this experiment our layouts were found to contain design errors which prevented the chips from working. The last batch of chips were far out-of-spec. This experiment is significantly more complicated than the MQC experiment. Nevertheless, it is extremely *less* complicated than many RSFQ experiments our group has succeeded to demonstrate in the past, and we have every reason to believe that we will be successful once more careful attention is paid.

NQI: We also have attempted to better understand quantum measurements by studying model systems, much simpler but in some ways analogous to our dc SQUID, in collaboration with G.C. Guo and his group at the University of Science and Technology of China. We have studied what we call "Nondistortion Quantum Interrogation," which is a subset of the more familiar "interaction-free measurement" (IFM) in which the quantum state of the object interrogated is left undisturbed. NQI could play future roles in quantum computing, in the extreme allowing that a "quantum computer can solve problems even without being switched on." [Proc. Royal Soc. London A 457, 1175 (2001)]

(6) List of all PUBLICATIONS and technical reports:

(a) Papers published in peer-reviewed journals

1. M.J. Feldman, "A Technique to Demonstrate Energy Level Quantization in a SQUID," *Physica B* **284**, 2127-8 (2000).
2. M.J. Feldman and M.F. Bocko, "A Realistic Experiment to Demonstrate Macroscopic Quantum Coherence," *Physica C* **350**, 171-6 (2001).
3. Pavel Rott and M.J. Feldman, "Characterization of Macroscopic Quantum Behavior using RSFQ Circuitry," *IEEE Trans. Applied Superconductivity* **11**, 1010 (2001).
4. R.C. Rey-de-Castro, M.F. Bocko, A.M. Herr, C.A. Mancini, and M.J. Feldman, "Design of an RSFQ Control Circuit to Observe MQC on an rf-SQUID," *IEEE Trans. Applied Superconductivity* **11**, 1014 (2001).
5. X. Zhou, J.L. Habif, A.M. Herr, M.J. Feldman, and M.F. Bocko, "A Tipping Pulse Scheme for a rf-SQUID Qubit," *IEEE Trans. Applied Superconductivity* **11**, 1018 (2001).
6. X. Zhou, Z.-W. Zhou, G.C. Guo, and M.J. Feldman, "High Efficiency Nondistortion Quantum Interrogation of Atoms in Quantum Superpositions," *Phys. Rev. A* **64** (Rapid Comm.), 020101 (2001).
7. X. Zhou, Z.-W. Zhou, M.J. Feldman, and G.C. Guo, "Nondistortion Quantum Interrogation using Einstein-Podolsky-Rosen Entangled Photons," *Phys. Rev. A* **64** (Brief reports), 044103 (2001).

(c) Papers presented at meetings, but not published in conference proceedings

1. M.J. Feldman, "RSFQ Control Electronics for Quantum Dynamic Systems," April 17, 2000, 6th Twente Workshop: New Devices and Circuits, University of Twente, Enschede, The Netherlands.
2. M.J. Feldman, "Control Electronics for Solid-State Quantum Computing," July 12, 2000, Progress In Electromagnetics Research Symposium (PIERS 2000), Cambridge MA.
3. X. Zhou, J.L. Habif, P. Rott, M.F. Bocko, and M.J. Feldman, June 9, 2001, "An Experiment to Observe Macroscopic Quantum Coherence in an rf-SQUID," at the International Conference on Quantum Information (ICQI), Rochester NY.
4. X. Zhou, Z.-W. Zhou, G.C. Guo, and M.J. Feldman, June 9, 2001, "Interaction-Free Measurements of Quantum Objects," at the International Conference on Quantum Information (ICQI), Rochester NY.
4. J.L. Habif, X. Zhou, M.F. Bocko, and M.J. Feldman, June 10, 2001, "A Tipping Pulse Scheme for an rf-SQUID Qubit," at the International Conference on Quantum Information (ICQI), Rochester NY.
6. X. Zhou, M.F. Bocko, and M.J. Feldman, June 11, 2001, "Isolation Structures for the Solid-State Quantum-to-Classical Interface," at the International Conference on Quantum Information (ICQI), Rochester NY.
7. M.J. Feldman, "Flux-based Superconducting Quantum Computing," June 11, 2001, at the International Conf. on Quantum Information (ICQI), Rochester NY.

(d) Manuscripts not published in conference proceedings

59. "Superconducting Electronics: Prospects for Digital and Quantum Computing," Andrea M. Herr, Ph.D. Thesis, Dept. of Physics, University of Rochester, March 1997.

(7) All participating scientific **personnel**, advanced degrees earned while employed this project.

PROFESSORS:	Prof. Mark F. Bocko
	Prof. Marc J. Feldman
	Prof. Alan M. Kadin

POSTDOCTORAL AND	Dr. Igor Vernik
RESEARCH ASSISTANT:	Dr. Cesar Mancini
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GRADUATE STUDENTS:

Dr. Andrea M. Herr	received the degree of Doctor of Philosophy in Physics
Dr. Cesar Mancini	received the degree of Doctor of Philosophy in Electrical Engineering
Mr. Pavel Rott	
Mr. Roberto Rey-de-Castro	
Mr. XingXiang Zhou	
Mr. Jonathan Habif	
Mr. Kevin Wright	

(8) Report of **INVENTIONS**: No reportable inventions