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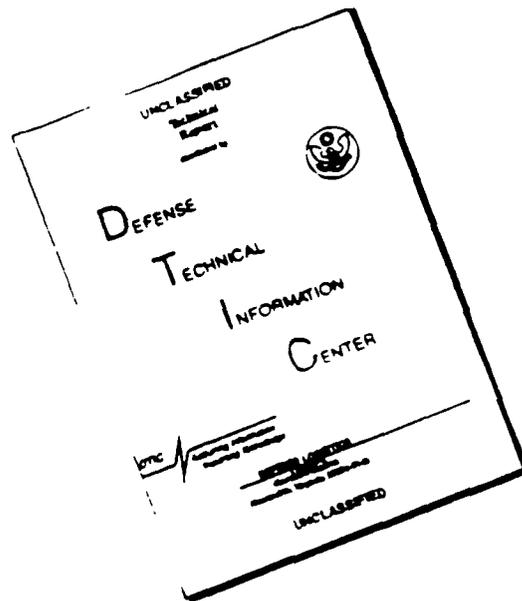


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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE August 1993	3. REPORT TYPE AND DATES COVERED Professional Paper
4. TITLE AND SUBTITLE STOCHASTIC RESONANCE IN A BISTABLE SQUID LOOP		5. FUNDING NUMBERS PR: MA19 PE: WU:	
6. AUTHOR(S) A. Hibbs, E. W. Jacobs, J. Bekkedahl, A. Bulsara		8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDT&E Division San Diego, CA 92152-5001		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 North Quincy Street Arlington, VA 22217		11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p><i>Stochastic Resonance (SR) is the name given to a statistical nonlinear phenomenon whereby a weak or subthreshold coherent function can be amplified by random forces, or noise, within the system. It was first advanced in the early 1980's as a possible explanation for the observed periodicities in the recurrences of the Earth's Ice Ages. The first publication of a modern theory led to an experiment and a flurry of further theoretical activity, an international conference and a review. In this paper, we describe a demonstration experiment wherein SR is exhibited in a superconducting quantum interference device (SQUID). Here SR is viewed as a noisy information transmission process. It is entirely appropriate, therefore, to look for this dynamic in a widely used sensitive detector; in this example, a detector of weak magnetic fields. Using a modern, miniature, thin film SQUID, we hope this demonstration will stimulate further research and development of SR in applied superconductivity.</i></p> <p>Published in <i>Noise in Physical Systems & 1/F Fluctuations</i>, AIP 285, 1993, pp. 720-723.</p>			
14. SUBJECT TERMS		15. NUMBER OF PAGES	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	
19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED		20. LIMITATION OF ABSTRACT SAME AS REPORT	

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21a NAME OF RESPONSIBLE INDIVIDUAL

A. R. Bulsara

21b TELEPHONE (include Area Code)

(619) 553-1595

21c OFFICE SYMBOL

Code 573

93-29770



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STOCHASTIC RESONANCE IN A BISTABLE SQUID LOOP

A. Hibbs

Quantum Magnetics, Inc., San Diego, CA, USA

E. W. Jacobs, J. Bekkedahl, A. Bulsara

Navy Command, Control and Ocean Surveillance Center, San Diego, CA, USA

F. Moss

University of Missouri at St. Louis, MO, USA

ABSTRACT

Stochastic Resonance (SR) is the name given to a statistical nonlinear phenomenon whereby a weak or subthreshold coherent function can be amplified by random forces, or noise, within the system. It was first advanced in the early 1980's as a possible explanation for the observed periodicities in the recurrences of the Earth's Ice Ages^{1,2}. The first publication of a modern theory^{3,5} led to an experiment⁴ and a flurry of further theoretical activity⁶⁻⁹, an international conference¹⁰ and a review¹¹. In this paper, we describe a demonstration experiment wherein SR is exhibited in a superconducting quantum interference device (SQUID). Here SR is viewed as a noisy information transmission process. It is entirely appropriate, therefore, to look for this dynamics in a widely used sensitive detector in this example, a detector of weak magnetic fields. Using a modern, miniature, thin film SQUID¹², we hope this demonstration will stimulate further research and development of SR in applied superconductivity.

INTRODUCTION

We have demonstrated *Stochastic Resonance*¹ in a bistable SQUID loop, as a first step in stimulating interest in possible applications using superconducting devices. We begin with an equation governing the magnetic flux trapped within an (f) SQUID loop¹³:

$$LC\ddot{\phi} + \tau_j \dot{\phi} + \phi + \frac{1}{2\pi}\beta \sin(2\pi\phi) = \phi_e, \quad (1)$$

where $\phi = \Phi(t)/\Phi_0$ is the normalized magnetic flux trapped within the loop, $\phi_e = \Phi_e(t)/\Phi_0$ is the normalized flux externally imposed on the loop, $\Phi_0 \equiv h/2e$ is the flux quantum, L and C are the loop inductance and junction capacitance respectively, and $\tau_j = L/R_j$ is the junction resistance. The parameter which determines the shape of the potential governing the dynamics of (1) is $\beta = 2\pi I_c \tau_j / \Phi_0$, where I_c is the junction critical current. In our experiment, the external flux Φ_e was composed of (b) periodic and stochastic components:

$$\Phi_e(t) = \Phi_{DC} + \Phi_{AF} \sin(\omega_c t) + \Phi_N(t), \quad (2)$$

where the periodic component represents an audio frequency signal, and the stochastic component was a Gaussian noise whose bandwidth was in the audio range¹⁴. Bistability is a prerequisite for observations of SR. Equation (1) is bistable for certain values of β and Φ_{DC} , and the quantity which shows the bistable dynamics is the flux trapped within the loop, $\phi(t)$.

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

In order to experimentally observe the bistable dynamics, one must measure the trapped flux $\phi(t)$. This requires a second SQUID, either mounted coaxially with the loop of the first SQUID, or coupled to it with a superconducting transformer¹⁵. We chose the latter configuration. The primary SQUID was a thin film device mounted on a single chip with integrally mounted, superconducting transformer primaries supplied by Quantum Magnetics. This is a thin film SQUID with primary and secondary windings coupled to the SQUID all evaporated on a single silicon chip. The Quantum Design DC SQUID chip is shown in Fig. 1. It is the first commercially available and the most sensitive all-thin-film DC SQUID sensor. The junctions, located in the central region of the chip, are made in the state-of-the-art niobium trilayer technology on silicon and are part of two two identical loops connected in parallel, each coupled to an input coil. This unique "double balanced" design reduces coupling between the input and modulation

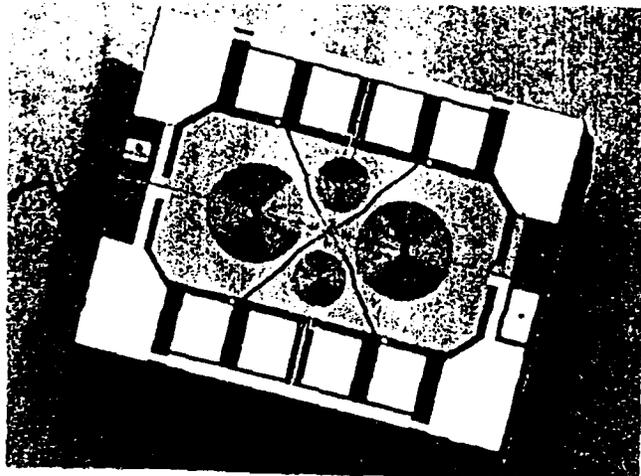


Fig. 1. The Quantum Design DC SQUID. The rectangles around the edges are bond pads for electrical connections. The left and right spiral coils couple the input signal to the SQUID loops. The upper and lower coils are used for a 500 kHz AC flux modulation used for noise reduction. The current and voltage leads appear as a cross but are not connected in the middle. The two Josephson junctions are located at the lower left and upper right of the cross but near the center. The size of the chip shown is 5 x 3 mm.

coils to negligible levels while giving high mutual inductance with the SQUID.

The secondary, or measuring, SQUID was a standard BTI model¹⁶, which was coupled to the primary SQUID with a completely superconducting transformer. A schematic diagram of the experimental setup is shown in Fig. 2. This apparatus was mounted inside a superconducting Nb shield and mounted near the bottom of a liquid helium dewar. The apparatus was operated at a temperature of 4.2 °K in boiling liquid helium. No further external magnetic shielding was employed.

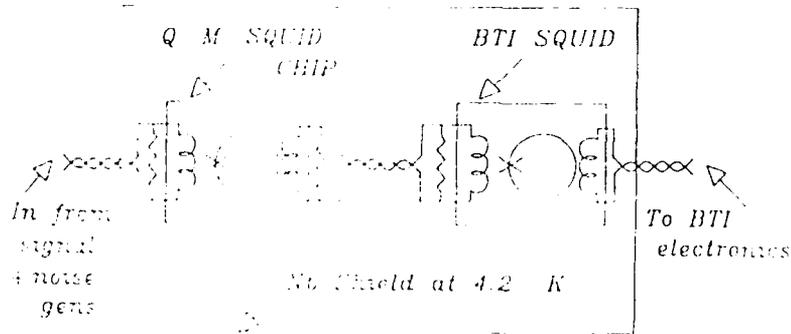


Fig. 2. Schematic of the bistable SQUID experiment showing the Quantum Magnetics chip and the BTJ measuring SQUID coupled with a superconducting transformer. Noise and signal voltages supplied by the external electronics were transformed into external magnetic flux in the coil C1.

EXAMPLE EXPERIMENTAL RESULTS

In our experiment, $\beta = 2.0$ and $\Phi_{pc} = 0.5\Phi_0$, values which guaranteed that the potential was bistable. Experiments were performed at two signal frequencies, 17.6 Hz and 100 Hz with signal peak voltages of 650 mV-pk and 475 mV-pk respectively. The noise, or stochastic, component was supplied by a standard noise generator and the noise voltage varied over the range from 100 to 1500 mV-rms. (1.0 V was equivalent to $0.1\Phi_0$ of applied external flux). The power spectra of $\alpha(t)$ were measured and averaged in the usual way at the output of the BTJ SQUID electronics, and the signal-to-noise ratios (SNR's) were determined from the measured and time averaged power spectra of the output of the BTJ electronics using a conventional definition. The results of this experiment are shown in Fig. 3 where the circles represent the results for the low signal frequency and the squares for the high frequency.

At each frequency, data were collected for two different signal strengths. For each data set, a clear maximum in the SNR - the familiar signature of SR - was observed. The maxima in the SNR occur at a noise voltage of ≈ 700 mV which is equivalent to an rms fluctuation of $0.07\Phi_0$ within which a coherent signal equivalent to $0.0237\Phi_0$ peak at 17.6 Hz was easily detectable. This clearly demonstrates that bistable SQUIDS, used in combination with SR, can be useful in detecting weak, coherent magnetic signals buried in external noise, an application of considerable importance.

Work supported by the U.S. Office of Naval Research grant N00014-91-J-1979 and by Quantum Magnetics, Inc.

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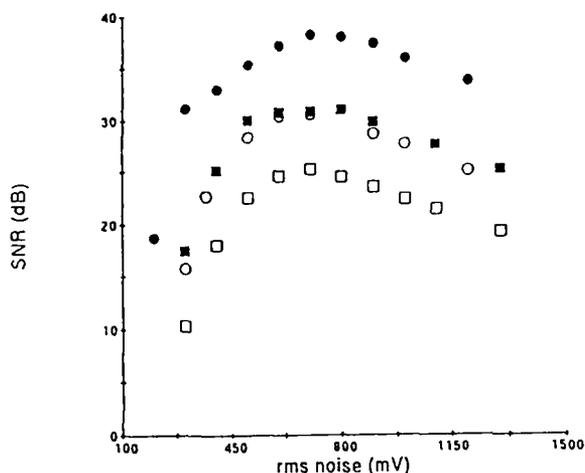


Fig. 3. The SNR versus rms noise voltage for the bistable SQUID experiment, with $f_s = 17.6$ Hz, $v_s = 650$ mV-rms (filled circles) and $v_s = 237$ mV (open circles); and $f_s = 100$ Hz, $v_s = 475$ mV (filled squares) and $v_s = 237$ mV (open squares). For these data 1.0 V $\equiv 0.1\Phi_0$ at the coil C1.

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