Abstract:

Arrays of nanoscale apertures on thin (~ 60 nm) silicon nitride membranes have been discovered to exhibit the characteristic signatures of so-called Josephson weak links in superfluid helium-4 (4He) [1]. These devices can be used to detect quantum phase differences in a matter wave interferometer made with two weak-links in a loop [2]. We summarize here our recent [3] observation of quantum interference (the characteristic pattern predicted for 4-slit optical interference) from a 4He grating structure consisting of four weak links. We also report here a new displacement sensor [4] that uses a rare-earth magnet attached to a flexible diaphragm for use in our superfluid experiments with the nanoscale aperture arrays. Some fabrication issues and outstanding questions are discussed [8].

Summary of Research:

I. Introduction: The superfluid Josephson effect refers to the strange phenomenon that occurs when two volumes of a quantum coherent fluid are connected by a passage (called a weak link) whose dimensions are a few tens of nanometers. If a pressure differential is applied across the apertures to force the liquid from one side to the other, the resultant motion is a flow oscillation at the “Josephson frequency.” This so-called “quantum whistle” was discovered in our laboratory in 2005 [1]. A “weak link” is analogous to a coherent source of light in optics. Just as two coherent light waves characterized by a phase difference interfere with each other to produce an optical interference pattern, superfluid matter-waves can interfere to produce an acoustic interference pattern that can be detected (and heard) using a sensitive displacement sensor. An arrangement with two weak-links in a loop therefore behaves as an interferometer (analogous to the superconducting quantum interference device, dc-SQUID) where the resultant amplitude of current oscillations varies nonlinearly with the difference in phase drops across the weak-links [2]. The phase difference $\Delta$ can be caused by (among other things) the Sagnac effect [5] (due to rotation of the loop) or by an artificially induced superfluid current using heat flow, which translates to a phase gradient for the superfluid wave-function. We explicitly demonstrated this in 2007 [6].

II. SHeQUIG (superfluid 4He quantum interference grating): Using this phenomenon, we have recently demonstrated—for the first time [3]—quantum inter-

Figure 1: Current oscillation amplitude vs. phase difference between adjacent weak-links in the grating. The solid line is a 2-parameter fit to a function describing the resultant of four unequal oscillations.
ference from a $^4$He grating structure consisting of four weak links placed in parallel in a loop filled with superfluid $^4$He. Figure 1 is an example of experimental data (at fixed temperature) of the total mass current oscillation amplitude as a function of $\Delta$. Note the striking similarity to a four-slit optical interference pattern. Further details may be found in [3].

III. New Displacement Sensor: In the past, we have used a displacement sensor system invented by Paik [7] to monitor the mass current oscillations mentioned above. This system (Figure 2a) uses a persistent current trapped in a SQUID circuit, and the motion of a superconducting metal-coated diaphragm changes the inductance of the circuit and registers a signal in a SQUID. The new displacement sensor (Figure 2b) reported here uses a small rare-earth magnet attached to a diaphragm. The magnet’s field creates a flux in the input coil of a SQUID. When the diaphragm changes position, the field from the magnet changes the flux in the pickup coil. The SQUID electronics outputs a voltage linear in the displacement of the diaphragm. Further details may be found in [4].

IV. Fabrication Summary and Issues: Very thin (~ 60 nm) freestanding membranes of silicon nitride are created on standard DSP silicon wafers using photolithography. Square arrays of apertures with varying separations and number with nominal sizes of 70 and 90 nm (see Figure 3 for an example) are then shot through these membranes using electron beam lithography. Each array acts as a single “weak link” in our experiments. The necessity for the membranes to be physically strong and survive thermal cycling to and from ~ 2K while ensuring the throughness of the apertures imposes several restrictions on the fabrication processes. There are several steps in our process where these requirements come into conflict. For instance, using chemical stripping to remove e-beam resist without stressing the windows can leave residues that clog the apertures—using a plasma to avoid this can wrinkle the windows and weaken them considerably. A balance can be sought by using a high pressure plasma in the Branson barrel etcher in small time steps to avoid over-heating. Further details of the fabrication process, more issues and their (partial) resolution can be found in [8].

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