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Cooled video camera for optical investigations below 1 mK

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An optical imaging system for milliKelvin temperatures has been developed based on a regular B/W surveillance camera (25 frames/s), with its CCD sensor inside the 4-K vacuum can of our nuclear demagnetization cryostat. The heat leak to the nuclear stage, caused by the operation of the video camera, was reduced below 1 nW by careful rf shielding. The construction of the system and its limits of operation are discussed.

The desire to obtain images of the ^{3}He superfluid phases below 3 mK has made it necessary to develop new optical measurement techniques. So far, cryostats with optical access from room temperature, through a set of 3 to 5 windows, have reached temperatures down to about 25 mK.[1,2] Recently, temperatures below 1 mK have been obtained in a setup where laser illumination was brought to 4 K by a single mode optical fiber and the image was transmitted out of the cryostat along a coherent bundle of 30 000 fibers.[3] In such an imaging system, the resolution is limited by the coherent fiber bundle since the amount of pixels in a CCD (charged coupled device)-type of camera is typically ten times larger than the number of fibers in the bundle.

Another scheme for milliKelvin imaging, pioneered by Wagner *et al.*,[4] is to employ a cooled CCD sensor inside the vacuum can immersed in liquid helium at 4 K. Since the dark current decreases exponentially with temperature, this allows the use of the so-called slow-scan mode which facilitates the observation of very weak light signals. The cooled slow-scan cameras have sweep frequencies around 100 kHz which results in rather slow read-out speeds, on the order of 1 frame/s.

In this Paper, we describe a milliKelvin temperature imaging system, based on a cooled CCD which operates a real-time video speed. We use in our setup a regular B/W surveillance camera (JVC, model TK-S 200) whose sensor (Matsushita, MN 3745, 518H×582V pixels) is capable of operating down to about $T=60$ K. One of the main problems in the remote operation of this CCD sensor is the phase shift of the clock signals, caused by the delay in the extended 1.5 m long electrical wires between the sensor chip and its room temperature control electronics. This distorts the gray scale of the picture severely. We have compensated for the phase shift by inserting two advanced CMOS gates, with a total delay of about 10 ns, into the clock signal line of the CCD read-out control (see Fig. 1).

The leads from the control unit to the sensor were installed into the pumping line of the vacuum can. Coaxial cables (type C1, 105 pF/m, Lake Shore, Westerville, Ohio) are used for the read-out signal and for the horizontal (10 MHz) and vertical (15 kHz) drives. The rest of the leads were made of 0.3 mm diam manganin wire, insulated by Teflon tubing. The six coaxial cables for the drives were slipped inside a greased copper braid that was employed for heat sinking at 4 K. To provide a separate electrical shield, the braid was grounded only from one point at its low temperature end. The same procedure was applied to the manganin wires. The CCD read-out line was shielded and grounded in a similar way but kept separate from the other coaxial cables.

The sensor itself was mounted on a circuit board located inside a tight cylindrical copper box (ϕ=35 mm, $L=35$ mm), as illustrated in Fig. 2. The upper end of the box has a hole of 7×10 mm^2 capped with a 2 mm thick fused silica thermal filter. A copper cold finger (ϕ=5 mm) connects the body of the box to the vacuum can flange immersed in the liquid He bath. In order to keep the CCD sensor at its lowest working temperature, around 70 K, the CCD chip was heat sunk, using grease secured with GE 7031 varnish, to a 0.6 mm thick temperature-controlled copper plate. An 80 mm long copper wire of 0.5 mm diameter provides the weak thermal contact between the plate and the cold finger. The power generated by the CCD chip itself was measured to be about 170 mW which is not enough to raise the temperature sufficiently; extra heating on the order of 150 mW is needed for proper operation of the CCD sensor.

Our optical setup is a modification of the scheme employed in Ref. 3. The He–Ne laser illumination is guided into the cryostat via a single-mode optical fiber. The beam is expanded to 10 mm diameter and directed by a beam splitter and by a set of mirrors through the cell. Only about 0.05% of the light is reflected to the camera from the sample, i.e., from the reference plate (reflection coefficient $R\approx 3\times 10^{-4}$) and from the free surface of liquid ^{3}He ($R\approx 2\times 10^{-4}$), while the rest of the illumination traverses the cell and is absorbed by the still radiation shield. A single bi-convex lens ($f=125$ mm) forms the interference image, created by the two reflected beams, to the CCD sensor.

In order to block the infrared radiation, emerging from the CCD sensor at 70 K, we installed two additional thermal filters, made of sapphire and CaF_2 (with thicknesses 2 and 8 mm, respectively), to the optical path leading to the sensor (see Fig. 2). These filters reduce the thermal radiation from the sensor to its surroundings below a few nanowatts.[5] The filters and windows used in our optical setup were antireflec-

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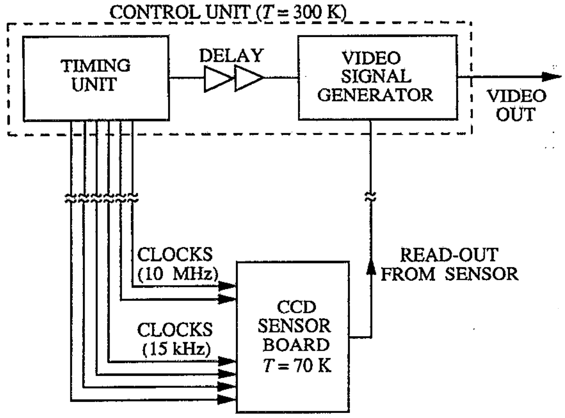

FIG. 1. Principal scheme of the remote-controlled CCD imager.

tion coated to avoid problems with secondary reflections.

Initially, heat leaks in excess of 1 μW were observed to the nuclear demagnetization stage when the camera was operated. This was assigned to rf heating caused by the 10 MHz digital signals entering the cryostat. Therefore, extreme care was taken to shield the milliKelvin parts against the rf radiation from the 10 MHz drive signals. We tried to make the inner radiation shield around the nuclear stage a true "Faraday cage." Ground loops due to the ^{3}He fill lines were broken inductively by six-turn spiral (ϕ=10 mm) sections, grounded from the middle when penetrating the shield. The only electrical wires entering the inner radiation shield are those needed to operate the heat switch and the pulsed platinum NMR thermometer. The leads of the heat switch magnet and of the Pt static coil (wound from CuNi-clad multifilamentary NbTi wire) have 47 nF ceramic capacitors to ground and across the lines at the entry point to shunt high frequency disturbances. The twisted pair for the rf coil is shielded by a Cu–Ni tube covered by tin solder. Because of limitations imposed by the tuning of the Pt tank circuit, only a 220 pF mica capacitor is connected across the leads of the rf coil. To eliminate possible electrical potential differences, we employ superconducting wire along the dilution refrigerator between the still and the mixing chamber.

Owing to our experimental needs we have two 12 mm diam holes in our "Faraday cage;" they do not seem to be too detrimental. One of them is along the axis of the cryostat and allows the laser illumination to enter the experimental space whereas the other lets the nonreflected light to escape from the coldest parts of the cryostat to the still radiation shield.

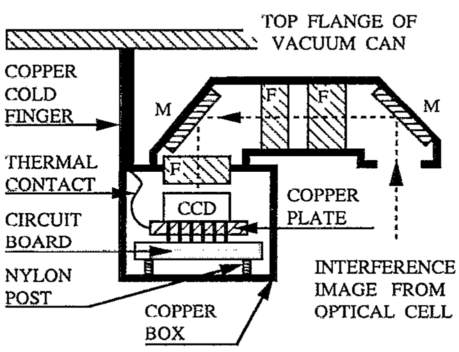

FIG. 2. Mounting of the CCD sensor inside the 4 K vacuum can. Cables connecting the circuit board to the control unit are not shown. F=thermal filter, M=mirror.

The basic heat leak of our nuclear demagnetization cryostat is 10 nW. Operation of the camera does not change this within an accuracy of 10%, i.e., the heat leak from the CCD is less than 1 nW. An additional source of heating is the laser light used for illumination. The sensitivity of our CCD is such that a light power of 40 μW is required for successful imaging. About 0.5% of the light is absorbed to the fused silica reference plate inside the experimental cell, which means a heat leak of 100 nW to the ^{3}He sample under investigation. We find that heat absorbed by the fused silica is transmitted to liquid ^{3}He with an effective time constant of 100 ms. Typically, we employ 20 ms light pulses. A repetition rate of 1 Hz results then in an average heat leak of 2 nW. For a bulk sample, this is not critical but with thin films a strong fountain effect is observed. Thus real-time imaging can be performed on bulk specimens over relatively short time intervals (a few seconds). This is, nevertheless, sufficient to study the surface dynamics of superfluid ^{3}He (Ref. 6).

To decrease the heat leak, laser light of lower power level would be preferable. One possibility is to enlarge the reflection coefficient of the reference plate but this leads to a degraded contrast in the interference image. The most straightforward solution would be to use a slow-scan camera which takes advantage of the small dark current at low temperatures. Thereby an increase by a factor of 100 in the light sensitivity could be obtained but the real-time imaging capability is lost. However, the light sensitivity of a regular CCD can also be improved by installing a separate, low-noise preamplifier to increase the S/N ratio at small illumination levels.

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