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Low-Temperature DC-Contact Piezoelectric Switch Operable in High Magnetic Fields

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Abstract

A piezoelectric single-pole single-throw (SPST) switch has been developed, since there is no satisfying commercial low-resistance, high current DC-contact RF switch available which is operable at 4.2 K and in a high magnetic field of at least 0.5 T. This piezoelectric switch shows very low insertion loss of less than -0.1 dB within a bandwidth of 100 MHz when operated at 4.2 K. The switch could also be used to mechanically disconnect and connect electrodes or electrical circuits from one another.

Keywords: cryogenic electronics, switches, radio frequency

1. Introduction

In low-temperature environments there is often the need to switch signals. A typical application is shown in Figure 1 where a Penning trap [1, 2] should be connected and disconnected to/from readout electronics. One use case is the phase sensitive-detection of the axial oscillation frequency of trapped particles, where detector decoupling (*sw1*) increases the achievable phase resolution significantly [3, 4]. Another application could be to disconnect the cryogenic ampli-

fier selectively with switch *sw2* in order to see if there is amplifier noise driving (heating) the trapped particles. In cryogenic environments it is important that a switch is not sealed with an inert gas atmosphere, which could freeze when cooled below its freezing point. The most direct solution for signal switching at cryogenic temperatures is to use, for instance, evacuated relays such as the Teledyne RF180 series or special cryogenic microelectromechanical systems (MEMS) switches [5]. An additional difficulty occurs when operating such switches in a cryogenic environment and a high magnetic field. Relays, which are in general switched by means of electromagnetic actuation, cannot operate in

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high magnetic field environments.

Figure 1: Typical application for a switch that electrically connects/disconnects the whole readout electronic chain (sw1) or the cryogenic amplifier only (sw2).

MEMS switches are operable if the used materials are non-magnetic and activation takes place by electrostatic potentials. Another technology, suitable for low-temperature application and high magnetic fields, are GaAs monolithic microwave integrated circuit (MMIC) switches. The disadvantage of MMIC switches is that their on-resistance easily reaches several Ω . An example is the GaAs switch SW-239 (M/A-COM Technology Solutions Inc.) which has an on-resistance of 2 Ω at 4.2 K. In order to reduce the on-resistance, several switches may be connected in parallel with each other but this reduces the isolation performance as well [6]. Moreover, a DC-contact switch does not induce additional noise and there are no nonlinearities in the transfer behavior compared to MMIC devices.

2. Experimental Details and Results

2.1. Switch Design

A single-pole single-throw (SPST) switch (see Figure 2 b)) made of a piezoelectric (piezo) activated bender (see Figure 2 a)), designed for cryogenic temperature and high magnetic field has been developed and characterized. The

piezo bender PL140.10 is made of a ceramic material – lead zirconate titanate (PZT) – and is produced by Physik Instrumente (PI) GmbH & Co. In ref. [7] the low temperature properties of this piezo bender made of two different ceramic materials (PI nomenclature: PIC251 and PIC255) were evaluated and it was shown that they work at 4.2 K with reduced deflection performance. Taking the nominal deflection of ± 1 mm at room temperature as reference, this deflection is reduced by a factor between 6.4 (PIC255) and 16.6 (PIC251) when cooled to 4.2 K [7].

The switch contact is realized by a 150 nm gold layer sputtered on the piezo bender (see Figure 2 a)) and the two permanent contacts of a Teledyne magnetic-latching radio frequency (RF) relay (RF180 series (see Figure 2 b)). The piezo bender and the relay contacts are mounted on an aluminum support. Since the RF relay is fixed directly on the aluminum surface, the leads have to be insulated by means of a polyimide (kapton) foil. The piezo bender is held by two screws and an aluminum bar (bottom right in Figure 2 b)).

Figure 2: a) Photograph of the piezo bender with the gold sputtered area. b) Photograph of the assembled piezo switch.

There was the need for an additional insulation layer (spacer) (see Figure 3) between the piezo bender surface and the gold contact

since the ceramic material introduces additional loss and the switch RF performance deteriorates (see Figure 4 a)). The spacer material is standard printed circuit board (PCB) laminate (FR-4) of about 0.34 mm thickness and it provides sufficient decoupling between the gold surface and the lossy piezo bender. In order to deflect the piezo bender, two DC voltages (V_{bias} and V_{switch}) have to be applied in the range of $0 \text{ V} \leq V_{\text{switch}} \leq V_{\text{bias}}$. The polarized piezoelectric layer deformation depends on the applied voltage V_{switch} , since V_{bias} has a fixed positive potential with respect to ground (0 V). Taking the piezo bender orientation in Figure 3 a), the electrical configuration of $V_{\text{switch}} = 0 \text{ V}$ and $V_{\text{bias}} = 40 \text{ V}$ deflects the piezo bender vertically downward and closes the electrical connection by touching the relay contacts. Applying $V_{\text{switch}} = V_{\text{bias}} = 40 \text{ V}$ moves the piezo element up, and the switch opens. The switch default position is $V_{\text{switch}} = V_{\text{bias}} = 0 \text{ V}$. In this case the bender is not polarized and its mechanical setup determines whether the switch is “normally closed” or “open”. Note that all measurements presented in this chapter were taken with a default closed switch.

2.2. Switch Characterization

The RF performance of the piezo switch was measured with the Agilent vector network analyzer (VNA) E8358A which had been full 2-port calibrated with the female SMA calibration kit 85033D. Since the system (VNA and cables) was calibrated at room temperature, the insertion loss trace is shifted to about +0.5 dB when cooled to 4.2 K (red trace in Figure 5 a)) due to the reduced loss. The shifted trace was obtained by replacing the switch by a short. This offset is

Figure 3: a) Electrical connection of the piezo bender in order to perform vertical displacement. b) Schematic of the piezo bender with sputtered gold surface on the bottom. c) Piezo bender with spacer glued to the bottom with gold surface on the spacer. Note that the spacer and the gold surface dimension is not to scale with respect to the piezo bender.

used in order to correct the measured insertion loss data of the switch at 4.2 K. The result shows an insertion loss of less than -0.1 dB within a 100 MHz bandwidth. The switch performance at low temperature was evaluated using a cryo-cooler measurement setup. Furthermore, the switch was evaluated in a high magnetic field of about 0.5 T without performance degradation. For this measurement the switch was placed in a room-temperature magnet bore and its switching behavior was investigated. Figure 4 shows the piezo switch RF performance with spacer at room temperature for open and closed positions. The insertion loss (IL) of the switch is below 0.2 dB within a bandwidth of about 100 MHz, and the isolation performance in this frequency band is limited by the capacitive coupling of the relay contacts (see Figure 4 b)). The switch is suitable for DC switching applications as well as for RF signals and has a DC on-resistance of less than $0.813 \text{ m}\Omega$ at 4.2 K and 0.162Ω at room

temperature. The DC resistance was evaluated in a 4-wire measurement in order rule out the wire measurement resistance. Due to the galvanic isolation and low switch capacitance, the switch has a high insulation. Note that the on-resistance was measured with the relay leads, thus the contact resistance is smaller than the aforementioned values.

Figure 4: Piezo switch RF performance at 290 K. a) Switch in closed position with and without spacer. b) Switch in open position (blue) and switch contacts without piezo bender.

The switch performance at cryogenic temperature is shown in Figure 5. Since the piezo bender has reduced deflection at 4.2 K there is the need to apply higher switching voltages compared to 290 K in order to obtain excellent isolation performance. While applying

$V_{\text{switch}} = V_{\text{bias}} = 40\text{ V}$ leads to an isolation of about -67 dB at room temperature and 20 MHz frequency (see Figure 4 b)), one has to apply $V_{\text{switch}} = V_{\text{bias}} = 100\text{ V}$ at 4.2 K (see Figure 5 b)) to reach the same isolation value.

Figure 5: Piezo switch RF performance at 4.2 K. a) Switch in default closed position $V_{\text{switch}} = V_{\text{bias}} = 0\text{ V}$ with and without correction as well as the reference trace (red) in order to correct the measured insertion loss (green). b) Switch in open position for $V_{\text{switch}} = V_{\text{bias}} = 80\text{ V}$ and 100 V .

3. Summary

This paper reports a low-loss switch designed for operation at 4.2 K and in high magnetic fields. The presented piezoelectric switch shows less than -0.1 dB loss at 4.2 K and is especially

suitable for signal switching in high-quality factor tuned circuit applications. The switch did not show performance degradation when operated in a magnetic field of 0.5 T, and its intrinsic properties should allow to switch even high current and high voltage, contrary to MEMS switches. There is a trade-off between the force a piezo element can develop and the displacement. The larger the force, the smaller the piezo bender and the more difficult the mechanical setup of the fixed contacts. The switch design presented in this work may be reduced in size by using a smaller piezo bender made of the material PIC255. This way, the reduced deflection upon cooling is less significant, and a smaller bender would show the same performance as the larger bender made of PIC251. Other designs, using linear motion piezo elements for instance, could work as well for electrical switching purposes. However, within this work only the switch design, using the piezo bender made of PIC251, was evaluated.

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