Notes on hysteretic crosstalk in 32-channel time-division SQUID multiplexer chips used in Keck and BICEP-2

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August 20, 2013

1 Introduction

We have recently come to understood that there is a very subtle form of crosstalk in some of the time-division SQUID multiplexer chips. This form of crosstalk is only seen when TES bolometers are attached to the inputs of the SQUID, so it was never observed in dip-probe measurements. It affects all SQUID mux chips with design numbers earlier than mux11d, including all 06 and 09 varieties. It does NOT affect the mux11d chips sourced for BICEP-3, and newer mux11e chips that are otherwise of similar design to those used in BICEP-2 and Keck.

The crosstalk affects an entire multiplexed column, and is caused by the fact that the feedback signal applied to the 'on' channel is also seen by the 'off' channels. The flux applied to the 'off' channels causes a back-action voltage across the 'off' TES bolometers, but this is usually a negligible source of crosstalk, since it is divided down by the large inductance in the Nyquist inductors.

However, as we now understand, there is an additional source of crosstalk caused by the fact that the 'off' channels can exist in two different flux states, and if the applied feedback flux is large enough, it can cause the channel to switch from one state to another. This is a hysteretic effect, with a hysteresis loop, and it can be switched back by switching the flux far enough in the other direction. This flux state is forgotten as soon as the chip is turned on, in which case it is single valued again. However, the back action from this switch of flux state can persist in the current flowing through the Nyquist inductor.

Below, I present a mathematical analysis of the effect, and compute a constraint on the first-stage SQUID designs to keep them single-valued when they are off, eliminating this hysteretic effect. All mux varieties from mux11d on satisfy this criterion.

2 Mathematical analysis of crosstalk

The ‘off’ SQUIDs also see the flux from the feedback signal applied to the ‘on’ SQUIDs. Call this flux Φ_{fb}.

The equation for the phase (ϕ, as opposed to Φ, which is flux) continuity around the SQUID loop with two Josephson junctions is:

$$2\phi_J + 2\pi(I_c L sin(\phi_J) + \Phi_{fb})/\Phi_0 = 2\pi n.$$

I_c is the critical current of a single Josephson junction.

Here ϕ_J is the phase across the Josephson junctions. It is the same in both junctions, since they carry the same current. We make the simplifying assumption that the two junctions have the same critical current. The phase across the junctions is $2\phi_J$, since there are 2 junctions.

There is also a phase-drop due to the magnetic flux in the SQUID loop. The first flux term is the ‘self’ field from the current flowing around the SQUID loop, which is $I_c sin(\phi_J)$, times the self inductance of the SQUID loop, L. Φ_0 is the flux quantum.

The second flux term is the applied flux from the feedback signal Φ_{fb}.

The macroscopic quantum wave function must be 2π periodic around the loop, so the right hand side has an integral number of 2π, where n is an integer.

The transcendental equation above can sometimes have more than one solution. This leads to flux hysteresis. When this occurs, as the feeback flux moves around as other pixels are operated, a flux quantum can enter one of the ‘off’ squids. Then, even though the feedback flux returns to the same value, the circulating current in the ‘off’ SQUID can be different, coupling a signal into the input circuit of the associated detectors. This could lead to a crosstalk term that would have two levels (since the high critical current SQUIDs presumably have two stable, and one metastable solution).

What are the conditions for this hysteresis? For very low critical current or self inductance, there is only one solution for the quantum interference equation above. However, as the self-field increases because the critical current or self inductance is increased, you can start having three solutions for n=1 (one of them being metastable). In the two-junction squid, this happens most readily when the feedback flux is zero. If the equation is single-valued for zero feedback flux, it is single-valued for all fluxes.

If the squid is multi-valued, then $d\phi_{tot}/d\phi_J$ will be equal to zero somewhere. If this never occurs, we will always be single-valued. The condition for this at zero feedback flux is thus:

$$\phi_{tot} = 2\phi_J + 2\pi(I_c L sin(\phi_J))/\Phi_0$$

or,

$\phi_{tot} = 2\phi_J + 2\pi\beta_L sin(\phi_J))$

where

$\beta_L = I_c L/\Phi_0$.

Then,

$d\phi_{tot}/d\phi_J = 2\pi\beta_L cos(\phi_J) + 2 = 0$

$\beta_L = -1/(\pi cos(\phi_J))$.

So if β_L is small enough, this cannot occur. Specifically, if

$\beta_L < 1/\pi$

the 'off' SQUID will be forever and always single valued, and this mechanism cannot occur.

So, what is the β_L of the mux06a and 09 SQUID used in BICEP-2 and Keck?

$I_c = 50\mu$A

$L = 20$ pH

$\Phi_0 = 2.068 \times 10^{-15}$ Wb

$\beta_L = 0.484$

Whereas
$1/\pi = 0.318$.

So the 1st-stage SQUIDs in mux06a, mux07a, mux09s, mux11c, etc. are *not* single valued.

3 BICEP-3 multiplexers

Here I show that the SQUIDs used in the mux11d chips intended for BICEP-3 do not have this source of hysteretic crosstalk. The target parameters for mux11d are:

$I_c = 5\mu A$

$L = 110pH$

$\beta_L = 0.266 < 1/\pi$,

So the mux11d's do not have this problem. We have tested some of these chips with TESs and see that the hysteretic crosstalk, as observed in x-ray pulses, is eliminated by this design. However, their parameters should be watched to make sure that they do not drift into this regime.