CMB Inflation Probe Technology Working Group

Polarization Modulation with Photolithographic Modulators

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Abstract: I briefly review the current status for MEMS and SIS switches for CMB polarization modulation. The devices remain at low TRL. Raising the TRL to TRL 5 would require 4 or more years development at funding levels $400K per year per project.

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1 Introduction

Reliable characterization of faint polarization superposed on a bright unpolarized foreground requires modulating the polarized signal on time scales short compared to instrumental drifts or $1/f$ noise. Of the various technologies studied in this workshop, microcircuit modulators offer the fastest modulation.

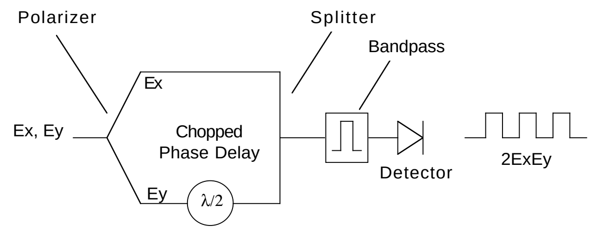

Figure 1: Schematic microcircuit polarimeter. A phase switch introduces a half-wave delay in one arm before the signals are combined and detected. The detector output has a dc term proportional to the unpolarized intensity (Stokes I) plus an ac term at the switch frequency proportional to the linear polarization. In practice, the circuit would be symmetrized with a 90° switch in each arm.

Figure 1 illustrates the concept for phase-sensitive microcircuit modulation. A polarizing microstrip element (e.g., orthogonal probes in a resonant structure) launches voltages into two arms of the polarimeter, proportional to the electric field amplitudes $E_x \cos(kz - \omega t - \phi_x)$ and $E_y \cos(kz - \omega t - \phi_y)$. A half-wave phase switch alternately injects a phase delay 0 or π in one arm. The voltages from the two arms are then combined before square-law detection. When the phase switch is off, the voltages in the two arms are

$$\begin{aligned} V_x &= E \cos\alpha \cos(\omega t - \phi_x) \\ V_y &= E \sin\alpha \cos(\omega t - \phi_y) \end{aligned} \tag{1}$$

where $E = \sqrt{(E_x^2 + E_y^2)}$ and α is the angle between the linearly polarized incident field and the xy coordinate system of the polarimeter. The detector power is

$$\begin{aligned} P_{\rm off} &= \langle (V_x + V_y)^2 \rangle \\ &= E^2 (1 + 2\cos\alpha \sin\alpha) \end{aligned} \tag{2}$$

up to an uninteresting constant phase. When the phase switch is on, it introduces an additional half-wave path length so that $V_y = E \sin\alpha \cos(\omega t - \phi_y + \pi) = -E \sin\alpha \cos(\omega t - \phi_y)$. The detector power is then

$$P_{\rm on} = E^2 (1 - 2\cos\alpha \sin\alpha) \tag{3}$$

As the switch chops, the detector produces a slowly-varying offset

$$\begin{aligned} P_{dc} &= (P_{\rm on} + P_{\rm off})/2 \\ &= E^2 \quad (i.e. \text{ Stokes I}) \end{aligned} \tag{4}$$

proportional to the unpolarized intensity, plus a rapidly modulated term

$$\begin{aligned} P_{ac} &= (P_{\rm on} - P_{\rm off})/2 \\ &= 2E^2 \cos\alpha \sin\alpha \\ &= 2E_x E_y \quad (i.e. \text{ Stokes U}) \end{aligned} \tag{5}$$

proportional to the linear polarization (Stokes U). We thus unambiguously separate the polarized and unpolarized components in a single measurement with a single detector. The concept can readily be extended to provide simultaneous measurements of the Stokes I, Q, and U parameters.

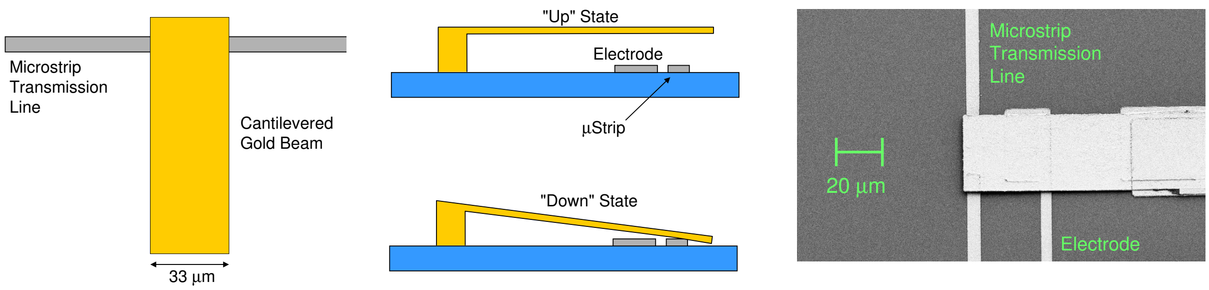

Figure 2: Schematic showing MEMS switch. (Left) Top view showing metal beam cantilevered above transmission line. (Center) Side view showing the beam in the "up" and "down" positions. (Right) Phase switches have reliably been fabricated using photolithographic techniques.

2 Current State Of The Art

Microcircuit polarization modulators require rapid phase modulation in individual arms of the circuit. Delay lines of different path length provide a simple, convenient way to produce the phase shift. To be practical for CMB polarization, the phase delay circuit should have low insertion loss (< 0.5 dB) and few-degree phase stability across the operating passband.

2.1 MEMS switches

Micro Electro Mechanical Systems (MEMS) switches are one technology for such a system. MEMS switches are miniature surface micromachined components providing controlled motion over a short distance to create either an open circuit or a short across a transmission line. Figure 2 shows the PAPPA MEMS switch. It consists of a metal beam 33 μm $\times$ 100 μm $\times$ 1 μm thick cantilevered 1 μm above the transmission line. An electrostatic voltage applied to a pull-down electrode pulls the beam down to short out the transmission line. Other designs are possible, including non-contacting designs which modulate the capacitance between the cantilever and the transmission line.

MEMS switches have been successfully incorporated into 90° and 180° phase modulators. Figure 3 shows the performance of the 90° phase modulator designed for the PAPPA instrument. The phase stability is excellent across a 30% band.

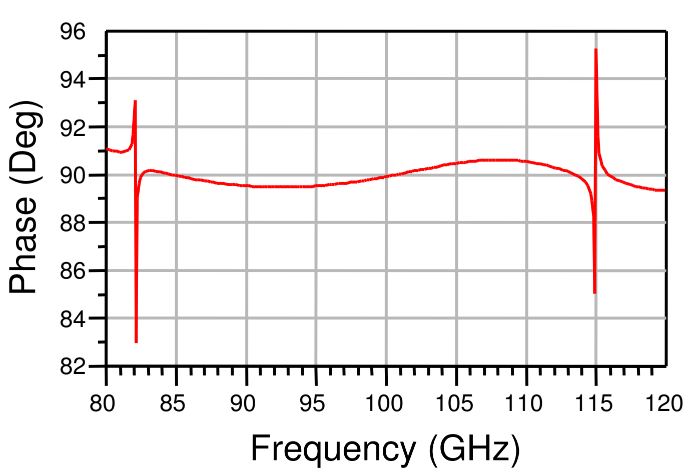

Figure 3: The 90° phase switch has 1° phase stability over a 30% bandwidth.

2.2 SIS switches

Superconductor-Insulator-Superconductor (SIS) junctions can also be used as the switching element for a microcircuit modulator. Figure 4 shows SIS switch efficiency measured at W band. Efficiencies of order 80% have been demonstrated across a 15% fractional bandwidth.

3 Advantages and Disadvantages

Both MEMS and SIS switches share a number of advantages and disadvantages for use in CMB polarimetry. Advantages include the following:

- **Scalable Technology** The switches are produced using the same photolithographic techniques on the same wafer as the detectors, and are scalable to kilo-pixel focal plane arrays. No hand assembly is required to produce multiple copies of a "polarimeter-on-a-chip."

- **Fast Modulation** Switching speeds are inherently rapid (100 Hz or faster). The actual speed is likely to be limited by the power dissipation per switching cycle, since the total dissipation from all switches must not exceed the available cooling capacity.

- **Repeatability** Once the initial switch design is tested and verified, performance variablility from one device to another should be small. This will reduce systematic effects associated with the overall circuit symmetry.

- **Cryogenic Reliability** There are no macroscopic moving parts (or for SIS switches, no moving parts at all), eliminating the risk associated with cryogenic mechanisms.

Disadvantages are dominated by the issue of complexity. Switch fabrication alone easily adds 10–20 steps (masking, deposition, etching, etc) to the photolithographic circuit production, with resulting higher costs and lower yields. In addition, the circuit design necessary to achieve broad-band ($\Delta\nu/\nu \geq 0.15$) signal switching is complicated both for design and verification.

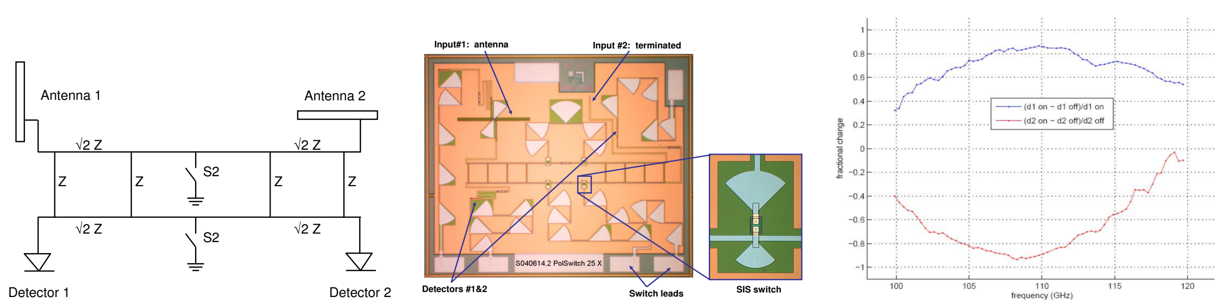

Figure 4: Demonstration of SIS switch. (Left) Circuit diagram for SIS test circuit. (Center) Photograph of fabricated circuit. (Right) Fractional signal modulation as the switches couple and decouple the detectors.

4 TRL Assessment

Largely due to the complications involved, these devices remain at low TRL. Phase-switched MEMS circuits have been demonstrated at GSFC and the University of Virginia, which retains a small program devoted to MEMS switch development. A prototype SIS switch has been demonstrated at JPL, but there is no longer an active program developing SIS switches. Both MEMS and SIS switches are currently at TRL $\sim$3.

Raising the modulators to TRL 5 would require 4 or more years development at funding levels roughly $400K per year per project. Both the time and cost are dominated by the fixed costs associated with photolithographic fabrication for multi-mask processes. Testing costs are sub-dominant compared to fabrication.