Measurements of a Cryogenic Linear Polarization Modulator for mm-Wavelengths

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***Abstract*—Cryogenic Faraday phase modulators have been implemented in waveguide and tested in both a constant current mode and an alternating current mode. The loss of the phase shifter for DC currents that results in either a $+90^\circ$ or -90° phase shift is on average 1.45 dB over the entire W-band. In the modulating mode, it operates at frequencies as high as 4 Hz with transition times between the two phase states of 1.32×10^{-2} s.**

***Index Terms*—Ferrite devices, modulation, superconducting magnet.**

I. Introduction

PHASE shifters are often used for steering phased array antenna beams and for radar applications [1]–[4]. They can also be used for modulating signals in radiometers and polarimeters. For astronomical measurements of mm-wave sources electronically controlled phase shifters are used in correlation radiometers (e.g., the WMAP satellite radiometers [5]) and in interferometers. The systems must often operate at background-limted sensitivity levels so the phase modulators must exhibit low loss. They must also be able to switch at frequencies above ~1 Hz to overcome 1/f noise in typical detector systems.

A particularly challenging application for phase modulators is in polarimeters for measuring the exceedingly faint polarization of the Cosmic Microwave Background (CMB) radiation. CMB polarimeters require multiple levels of modulation of the polarization signal. In order to reduce loss and minimize thermal emission from these modulators, cryogenic operation is typically required. Rotating half-wave plates have been used in several CMB experiments. However, modulators with moving parts are undesirable for cryogenic or space applications because of concerns about reliability and microphonic effects on sensitive detectors. Among the other candidate methods of polarization modulation for future CMB satellite missions are MEMS and SIS switches, which are complicated to fabricate, PIN diode switches [5], [6], which have relatively high loss, the Variable-delay Polarization Modulator (VPM), which requires only small linear motions, and the Faraday rotation modulator (FRM), which has no moving parts [7]. Since the FRM is a superconducting device, it naturally operates at temperatures $\lesssim$4 K.

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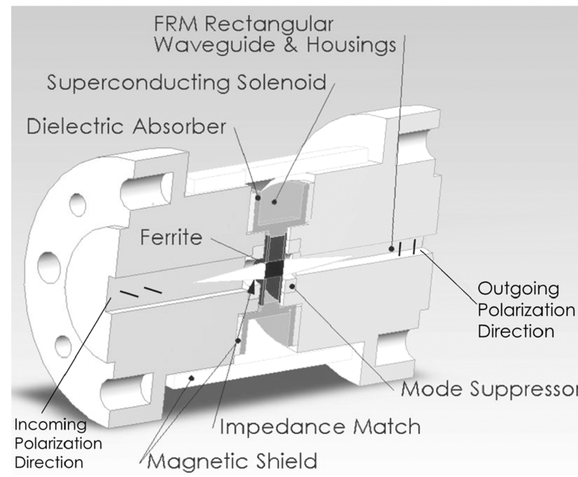

Fig. 1. Cross section of FPM. Alumina tapers impedance match the ferrite to circular waveguide which transitions to rectangular waveguide at the input and output flanges. The rectangular waveguide at the output is rotated 90° with respect to the input waveguide.

We have developed a Faraday phase modulator (FPM) based on the FRM for modulating signals in an interferometer optimized for measurements of the CMB. These FPMs are used in the Millimeter-wave Bolometric Interferometer (MBI) [8] to allow phase sensitive detection of signals produced by individual baselines, which requires modulation to occur before detection. Each baseline has a unique modulation frequency. This application requires square-wave switching between discrete phase values rather than a continuously controllable phase shift. Details of the modulation scheme and signal recovery can be found in [9] and [10]. MBI requires phase switches with rectangular input and output waveguides and discrete, electronically controlled phase shifts of $\pm 90^\circ$. A similar technique will be used in the upcoming QUBIC instrument [11] for CMB measurements.

II. Design

The FPM is a modified version of the FRM used in the BICEP CMB instrument [12], [13]. We have adapted them for use as linear polarization phase modulators. These preliminary test devices consist of rectangular waveguide flanges on each end that couple to a ferrite rod centered inside a circular waveguide surrounded by a super-conducting coil, as seen in Fig. 1. When the linearly polarized signal enters the ferrite, the left-circular and right-circular polarized components propagate at different speeds within the ferrite. The outgoing signal is then phase shifted based on how much one polarization component is retarded with respect to the other while traversing the ferrite.

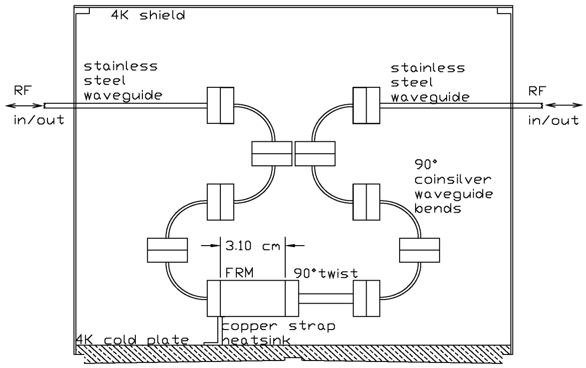

Fig. 2. Waveguide plumbing inside the 4 K dewar shield. Thin-wall stainless steel waveguides (0.03 cm thick) provide thermal isolation between the coin silver waveguides and FPM at 4 K and the dewar shell at 300 K. They are also heat sunk to the dewar's 77 K radiation shield. Thin plastic films act as vacuum windows (not shown).

The relationship between the phase shift and the magnetic field strength is given by

$$\phi = VBd \tag{1}$$

where ϕ is the angle of rotation of the polarization (in radians), V is the Verdet constant for the material, B is the magnetic flux density, and d is the length of the ferrite ($d \simeq \lambda_o/2$ with $\lambda_o = 3$ mm). The phase shift depends on the strength of the magnetic field produced by the surrounding coil, which depends on the current through the wires. Modulating the signal thus only requires changing the current supplied to the phase modulator. This allows for reliable modulation without any moving part. Previous tests on modulators with circular waveguides show a rotation of approximately 75° for input currents of a maximum of 340 mA. Since MBI requires phase rotations of ±90°, the rectangular waveguides on our modulators are set perpendicular to each other, so that only the E-field component which is rotated to be perpendicular to the input passes through the output (while the component parallel to the input is reflected back).

III. Test Setup

The FPM was tested in vacuum in a liquid Helium test dewar (Fig. 2) outfitted with stainless steel and coin silver WR-10 waveguide. The electrical connections to the FPM are made through 0.058 cm diameter brass wires heat sunk to the 77 K plate and the 4 K plate. They are downsized to 0.051 cm diameter copper wires to connect with the FPM. Three Lake Shore DT-500 silicon diode thermometers were connected to a flange of the FPM, the 4 K cold plate, and the waveguide plumbing near the steel waveguide. Temperature was read out with a Lake Shore 218 Temperature Monitor. Cool down of the dewar to a cold plate temperature of 4 K took ~3 hours and the temperature could be maintained for a few hours without refilling the liquid helium tank.

IV. Results

The FPMs can operate in two modes: steady state, where a constant current is applied to the device; and modulated, where a changing current is applied to the device. Tests were conducted in both modes.

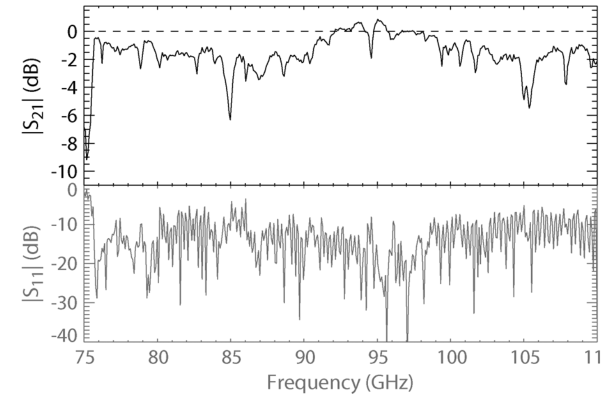

Fig. 3. Average value of $|S_{21}|$ at the maximum negative current of -375 mA is -1.45 dB. Corrections for the waveguide baseline subtraction are overestimated in the central portion of the band by at least 0.87 dB.

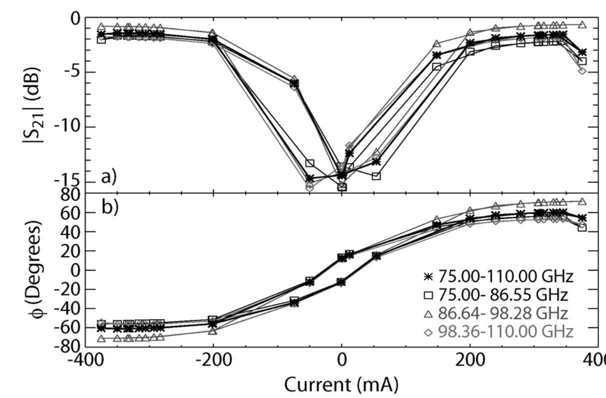

Fig. 4. FPM transmission and phase shift vs. current corrected for losses in the waveguide and ferrite and separated into 3 frequency bins and a full band average. The FPM shows the best transmission above 200 mA of applied current. The phase shift is estimated by applying (2). Over the entire frequency band, the FPM achieves between 60 to 80° of rotation.

A. Steady State

The S-parameters were measured (Figs. 3, 4) with an Agilent 8510C Vector Network Analyzer (VNA).

Measurements were taken over a range of input currents from -375 mA to $+375$ mA. For currents in excess of 300 mA, the coil warms and the steady-state temperature of the FPM rises above the cold plate temperature. At currents above 400 mA, the coil exceeds its superconducting transition temperature. Corrections for waveguide losses within the waveguide plumbing were made by taking a cold baseline measurement with the Faraday modulator replaced by a length of coin silver waveguide.

The device operates similarly for positive and negative currents of the same amplitude. Due to the magnetic hysteresis of the ferrite, some signal will still be rotated and pass through the output flange of the device even when no current is being applied. For higher currents, the transmission increases. At -375 mA, the average transmission across the band is -1.45 dB, as seen in Fig. 3. Fig. 4 summarizes these variations of response with frequency and current. Fig. 4 illustrates the variation of transmission for the full range of currents split into three frequency bins and an average over the full band. To estimate the amount of rotation occurring within the device from (1), a transformation between $|S_{21}|$ and angle is made using

$$\phi(i) = \frac{180}{\pi} \arcsin\left(S(i)\right) \tag{2}$$

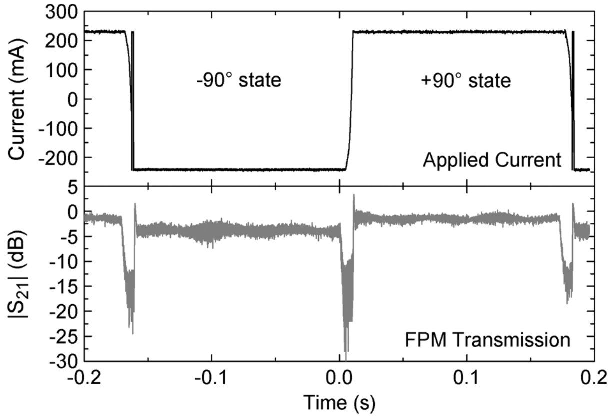

Fig. 5. Applied current: Current modulation pattern provided to the FPM to switch between the nominal $\pm 90^\circ$ states. FPM Transmission: RF signal at 90 GHz during this modulation.

where $S(i)$ is the $|S_{21}|$ at a given current i corrected for waveguide and ferrite losses and $\phi(i)$ is the resulting rotation angle estimate. Fig. 4 indicates that over the entire frequency band, the Faraday modulator achieves $\pm 60 - 80^\circ$ of rotation.

B. Modulated

The performance of the Faraday modulator was evaluated during current modulation with a maximum current of ± 230 mA. The transition time between states of the square-wave is also important as any time spent in transition between states reduces the instrument sensitivity. The upper panel in Fig. 5 shows the applied square wave modulation current provided by the control electronics to the Faraday modulator. Spikes in the applied current are due to ringing of the superconducting solenoid due to its high inductance. Another important quantity is the signal transmitted through the modulator while it is operating. Measurements were taken at several frequencies over the operating range of 75–110 GHz. The lower panel in Fig. 5 shows the transmission for a 90 GHz signal. Comparing the lines, it can be seen that the spikes correspond to times when the current is switching from a positive to negative sense. The time for the transition is 7.24×10^{-3} s for the control electronics and 1.32×10^{-2} s for the FPM when at a modulation frequency of 3 Hz. The imbalance in the transmission for the positive direction compared to the negative direction is directly related to the imbalance in the currents output by the control electronics and can be minimized by adjusting the current. Difficulty arises when attempting to modulate the device above $\sim$4 Hz. Eddy current heating raises the temperature of the superconducting coil above the threshold for superconductivity at $\sim$4 K.

V. Conclusion

The Faraday phase modulator is an effective modulator with no moving parts for low modulation frequencies. The average loss of the device over the waveguide band is 1.45 dB when at a maximum input current of ± 375 mA. Operation as a modulator is robust up to frequencies below a few Hertz. Eddy current heating causes these superconducting devices to over heat at higher frequencies. Better heat sinking of the superconducting coil can reduce heating and allow higher modulation frequencies.

In MBI-4 [8] the loss from the FPMs is comparable to other loss in the detector system (from filters, etc.). Of the four devices tested, one was able to sustain operation at $\sim$3 Hz for $>$2 minutes. Simulations of possible mechanical construction errors are necessary to identify the source of the inconsistencies between devices. Refining the design of the FPMs to give a full $\pm 90^\circ$ rotation would reduce the loss to $\sim$0.7 dB and could reduce any variation in performance due to the modulators being hand assembled.

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