Cryogenic Ka-Band 180° Phase Switch Based on Schottky Diodes

Enrique Villa, Beatriz Aja, Juan L. Cano, Luisa de la Fuente, *Member, IEEE*, and Eduardo Artal, *Member, IEEE*

***Abstract*—A Ka-band hybrid 0/180° phase switch working at cryogenic temperature is presented. The circuit is designed on an alumina substrate using uniplanar hybrid technology, combining air-bridged coplanar waveguides and slotlines. Schottky diodes are used as switching elements, taking advantage of their cryogenic behavior, with low equivalent series resistance and low capacitance. Cryogenic performance at 15 K shows a phase difference response of $177 \pm 2°$, average insertion losses of 1 dB and amplitude imbalance of less than 0.2 dB between states in the frequency range from 24 to 37 GHz (40% relative bandwidth) with a low-power consumption of 10.5 mW. The low insertion loss and small phase error make the designed phase switch suitable to be used on radioastronomy receivers (QUIJOTE experiment 26–36 GHz band) minimizing the total system noise temperature.**

***Index Terms*—Broadband, coplanar-to-slotline transition, cryogenics, millimeter wave, phase switch, Schottky diodes, uniplanar circuit.**

I. Introduction

PHASE switches (0°–180°) are common devices used for many different applications such as radioastronomy receivers, where they are required to have a broadband response [1]–[3]. In the radiometers, these circuits switch between the different receiver branches, thus enabling the cancelation of low frequency fluctuations of gain and noise temperature generated by the amplifier stages, and therefore, the reduction of the 1/f noise, which could mask the measured signals [4], [5]. In order to effectively achieve this reduction, the phase switches need to be one of the first subsystems in the receiver; therefore, they are usually cooled to cryogenic temperatures together with the low-noise amplifiers. However, the operation under cryogenic conditions imposes additional requirements that need to be taken into account: low power consumption is required for avoiding receiver internal heating, and low transmission loss is mandatory for minimizing its contribution to the system noise temperature.

Several types of phase switches have been implemented for radioastronomy applications. MMIC designs in microstrip line circuits, based on InP HBT technology, are reported in [6], and, with InP HEMT transistors, in [7]. An alternative design based on MEMS technology using an ohmic contact single-pole-double-through (SPDT) switch in coplanar waveguide (CPW) structure is described in [8]. These designs show wideband response, from 20% to 35% relative bandwidth, with less than 10° error in ideal 180° phase shift, and around 2 dB of insertion losses. However, their performances at cryogenic temperature have not been individually reported.

Manuscript received August 19, 2011; accepted December 05, 2011. This work was supported by the Spanish Ministry for Science and Innovation under the project AYA2010-21766-C03-03 and the CONSOLIDER-INGENIO 2010 programme under the reference CSD2010-00064.

The authors are with Department of Communications Engineering, University of Cantabria, Santander 39005, Spain (e-mail: enrique.villa@unican.es).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2011.2179920

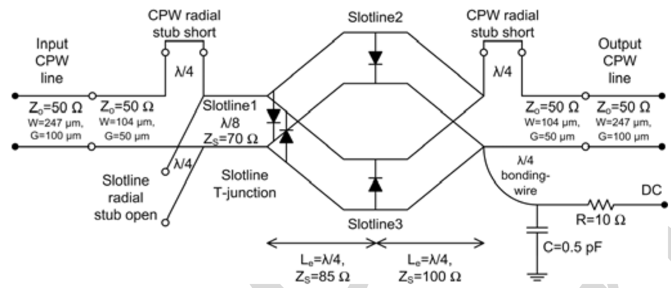


Fig. 1. Phase switch schematic.

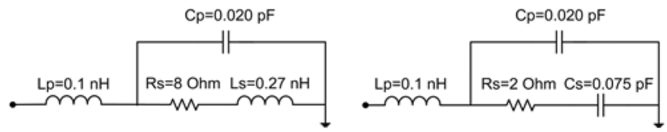
This work presents a hybrid phase switch design using uniplanar technology under cryogenics, showing a good electrical performance by using Schottky diodes. The circuit designed, aimed at using in QUIJOTE receivers [9] covering the frequency band from 26 to 36 GHz, shows a competitive solution which reduces manufacturing costs and time regarding the monolithic cases, and it is suitable for other radioastronomy bandwidths providing similar performance considering losses.

II. Phase Switch Design

A. Circuit Design

The circuit design is based on the use of finite ground CPW (FGCPW) lines transitioned to slotline. This configuration forms a uniplanar circuit with no backside metallization, and facilitates the introduction of diodes used as switching devices into it. To obtain the 180° phase shift, two pairs of diodes, assembled in antiparallel configuration and controlled by a dc signal, are used. A schematic of the phase switch is shown in Fig. 1, where the circuit configuration and position of the diodes are depicted. In the FGCPW lines, air-bridges eliminate their multimodal behavior, propagating only the even CPW mode. The circuit has reciprocal behavior. Its principle of operation is described in [10].

Among the different available substrates, alumina was selected due to some adequate characteristics. Its thermal conductivity of 7 W/(m·K) at 10 K, in comparison with a thermal conductivity of 0.1 W/(m·K) at 10 K of Teflon-based substrates [11], made it a better option. Its 3 μm conductive layer faced with the 17 μm thickness of Teflon-based made it more suitable for the etching of the narrow conductors and gaps of the transmission lines.



(a) (b)

Fig. 2. Schottky diode equivalent circuit at 15 K: (a) forward bias; (b) reverse bias.

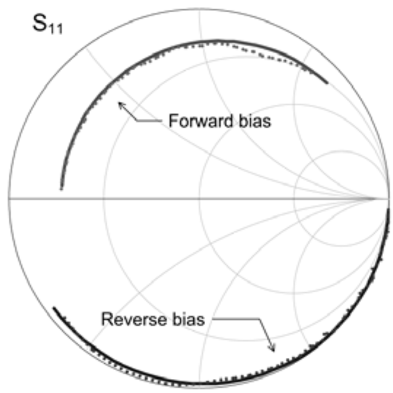


Fig. 3. Measured S_{11} for the Schottky diode to ground at 15 K over the frequency range 1–40 GHz: measurement in dotted line, model simulation in solid line.

B. Switching Device Characterization

Traditional switches at microwave frequencies were designed using discrete PIN diodes, implemented on silicon technology, as in [12]. Silicon devices show an unsuitable behavior under cryogenics, in terms of huge dc power consumption. Moreover, the poor reverse recovery time of these discrete devices limits the switching frequency rate. Therefore, taking into account the intended low-power characteristic, the switching device used to provide the 180° phase shift in the designed circuit, at cryogenic temperature, is a Schottky diode.

The diode must exhibit a low series resistance in forward bias, whereas having a low capacitance in reverse. The Schottky diode model MA4E2037 from MACOM is chosen as the switching component. Since the manufacturer did not provide data about its cryogenic behavior, it was characterized at cryogenic temperature in order to obtain its circuit model, and simple resistor-inductor and resistor-capacitor models were used for the Schottky junction, based on previous experience with diodes.

The diode was measured in a cryogenic probe station, using a dedicated TRL kit with CPWG-to-microstrip transitions. Fig. 2 shows the ON-OFF equivalent model for the diode including its parasitic elements $(\mathrm{L_p}, \mathrm{C_p})$, fitting the measurement in the frequency range from 1 GHz up to 40 GHz shown in Fig. 3 at 15 K. The diode was biased under cryogenic conditions with a current of 5 mA, having the phase switch a total current consumption of 10 mA in each state.

III. Module Design and Assembly

The circuit was assembled in a metallic chassis with coaxial connectors. The chassis was manufactured in brass, which has a thermal conductivity of 10 W/(m·K) at 10 K, and it was gold plated. For the temperature characterization during the test campaign, a temperature sensor is attached to the chassis, where

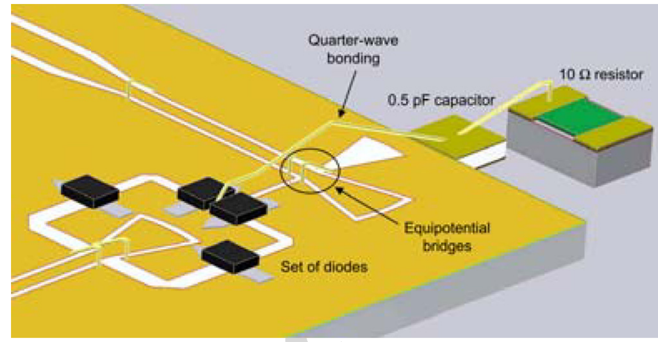


Fig. 4. Detailed schematic of the assembly and the bias circuitry.

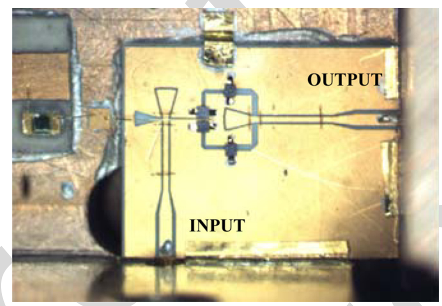


Fig. 5. General view of the phase switch assembly inside the module. Alumina dimensions: 5.93 mm × 4.58 mm.

a negligible temperature gradient between the circuit and the sensor is assured by its high thermal conductivity.

An empty cavity, larger than twice the substrate thickness deep, was machined under most of the substrate in order not to degenerate the slotline mode in the circuit. A reference plane under the 10 mil thick substrate would do the slotline transmission line works improperly. In order to avoid cracks during thermal cycles, an indium-based solder paste, which produces a soft joint by its high thermal conductance at cryogenics [13], and sliding contacts in the coaxial-to-CPW transition were used in the assembly.

The assembly was completed with the bias circuitry, which enables the modulation of the diode operation point (forward or reverse state), and previously tested under cryogenic conditions. The connection of the bias circuit is done through a quarter-wavelength bonding wire. Fig. 4 shows a detailed schematic of the bias network and bridges in the junctions. A view of the assembly of the whole circuit is shown in Fig. 5.

IV. Circuit Characterization

Phase switch characterization was carried out both at room and cryogenic temperatures. Outstanding performance was achieved working at cryogenic temperatures.

A precise cryogenic S-parameters measurement inside the cryostat is difficult to perform because there is no direct access to the device under test ports, so the setup used established the reference plane outside the cryostat and, then, the insertion losses of the 2.4 mm cryostat coaxial accesses were deducted, which were previously characterized in a cool-down cycle in a back-to-back configuration, connecting a short coaxial line between them, whose losses were negligible. Then, by a standard de-embedding procedure, the insertion losses of the circuit were calculated. The phase response was obtained without applying

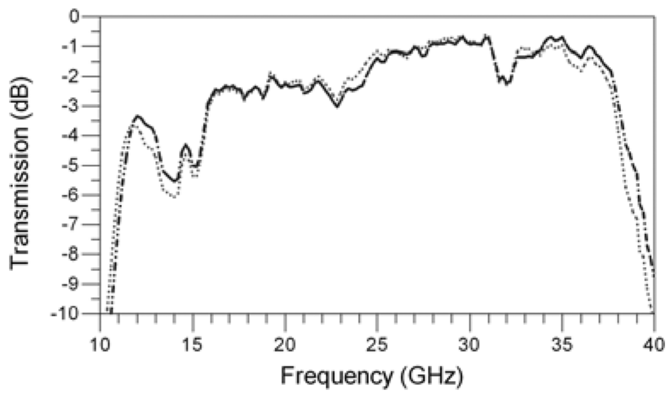


Fig. 6. Transmission losses for both circuit states.

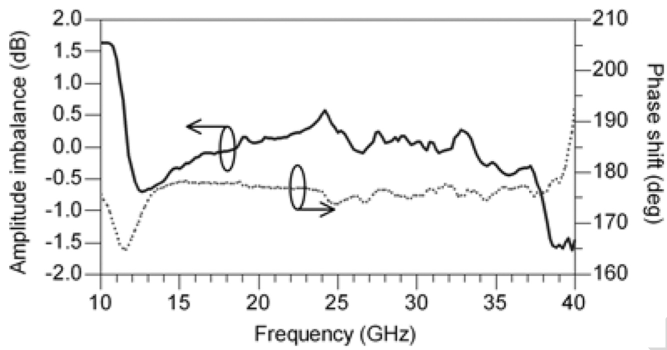


Fig. 7. Amplitude imbalance (left axis, solid line) and phase shift (right axis, dotted line).

TABLE I
PHASE SWITCHES PERFORMANCE

Reference	Frequency (GHz)	Insertion Loss (dB)	Phase Shift (º)	Technology
[6]	*30/44/70/100 (20%)*	*2 / 2 / 3 / 5 @ RT*	*180±1/±1/± 4/±5*	*MMIC InP HBT*
[7]	*26-36 (32%)*	*3.5 @ RT*	*170±10*	*MMIC InP HEMT*
[8]	*14-20 (35%)*	*2 @ RT*	*180±5*	*MEMS*
This work	*24-37 (40%)*	*2.1 @ RT 1 @ CT*	*177±2 @ RT,CT*	*Schottky diodes*

RT=Room temperature (300 K); CT=Cryogenic Temperature (15 K).

de-embedding technique, since it is a relative measurement between states.

Phase switch losses in both states are shown in Fig. 6, whereas Fig. 7 shows the amplitude imbalance and phase shift between states. The total power consumption of the circuit at 15 K was 10.5 mW.

Finally, Table I shows a comparison between results achieved in this work and other phase switches found in the literature. The design in this work shows a higher fractional operating bandwidth than referenced works, whereas insertion loss level is around 1 dB at cryogenic temperature using a hybrid technology; the circuit provides a very flat phase shift response at cryogenic temperatures.

V. CONCLUSION

A 180° phase switch designed in hybrid technology and working at cryogenic temperatures with Schottky diodes is presented. Its cryogenic performance was tested at 15 K showing a phase difference of 177 ± 2° and average insertion losses of 1 dB with amplitude imbalance of less than 0.2 dB between states in a frequency band from 24 to 37 GHz (more than 40% relative bandwidth). The 180° phase shift response of the circuit can be extended to cover the band from 16 to 38 GHz (80% relative bandwidth) with balanced insertion losses of less than 3 dB. These results validate the use of the Schottky diode MA4E2037 as a switching device at cryogenic temperatures, due to its low power consumption, low series resistance in forward bias and low capacitance in reverse bias.

ACKNOWLEDGMENT

The authors would like to thank A. Pérez and E. Cuerno, Department of Communications Engineering, for their assistance in circuit assembly, S. Cembellín, Cantabria Institute of Physics (IFCA), for chassis manufacture, and D. Bruch, Fraunhofer-Institut für Angewandte Festkörperphysik (IAF-Freiburg, Germany), for assistance with the Schottky diode measurement.

REFERENCES

[1] B. Aja, E. Artal, L. de la Fuente, J. P. Pascual, A. Mediavilla, N. Roddis, D. Kettle, W. F. Winder, L. Pradell, and P. de Paco, "Very low-noise differential radiometer at 30 GHz for the PLANCK LFI," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 6, pp. 2050–2062, Jun. 2005.

[2] R. J. Davis *et al.*, "Design, development and verification of the 30 and 44 GHz front-end modules for the planck low frequency instrument," *J. Instrum.*, vol. 4 T12002, pp. 1–36, Dec. 2009.

[3] P. Kangaslahti *et al.*, "Planar polarimetry receivers for large imaging arrays at Q-band," in *IEEE MTT-S Int. Dig.*, Jun. 2006, pp. 89–92.

[4] N. C. Jarosik, "Measurements of the low-frequency-gain fluctuations of a 30-GHz high-electron-mobility-transistor cryogenic amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 44, no. 2, pp. 193–197, Feb. 1996.

[5] E. J. Wollack, "High-electron-mobility-transistor gain stability and its design implications for wide band millimeter wave receivers," *Rev. Sci. Instrum.*, vol. 66, no. 8, pp. 4305–4312, Aug. 1995.

[6] R. J. Hoyland, "A new MMIC, wideband 180' phase switch design for millimeter wave applications," in *Proc. 3rd ESA Workshop Millimetre Wave Technol. Appl.*, Espoo, Finland, May 2003, pp. 305–310.

[7] D. Kettle, N. Roddis, and R. Sloan, "A Ka-band InP MMIC 180' phase switch," *IEEE Microw. Wirel. Compon. Lett.*, vol. 15, no. 6, pp. 425–427, Jun. 2005.

[8] M. A. Llamas, D. Girbau, M. Ribó, L. Pradell, A. Lázaro, F. Giacomozzi, and B. Margezin, "MEMS-based 180' phase switch for differential radiometers," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 5, pp. 1264–1272, May 2010.

[9] J. A. Rubiño-Martín *et al.*, "The QUIJOTE CMB experiment," in *Highlights of Spanish Astrophysics V, Astrophysics and Space Science Proceedings*. New York: Springer, 2010, pt. 3, pp. 127–135.

[10] E. Villa, B. Aja, L. de la Fuente, and E. Artal, "Wideband uniplanar 180° phase switch," *Electron. Lett.*, vol. 45, no. 11, pp. 556–557, May 2009.

[11] N. J. Simon, "Cryogenic Properties of Inorganic Insulation Materials for ITER Magnets; A Review," NIST, Boulder, CO, Tech. Rep. 5030, Dec. 1994.

[12] G. H. Behrens, Jr., "Cryogenically cooled C-band p-i-n diode integrated switch matrix for radio astronomy applications," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-26, no. 9, pp. 629–635, Sep. 1978.

[13] R. Radebaugh, "Thermal conductance of indium solder joints at low temperatures," *Rev. Sci. Instrum.*, vol. 48, no. 1, pp. 93–94, Jan. 1977.