Wideband uniplanar 180° phase switch

E. Villa, B. Aja, L. de la Fuente and E. Artal

A wideband 180° phase switch is developed at millimetre-wave frequencies (31 GHz centre frequency) using uniplanar technology. The circuit is designed using coplanar-to-slotline transitions and commercial *pin* diodes as switching devices. The implementation is straightforward, fast in terms of fabrication and low-cost. The circuits tested, made on an alumina substrate, show a phase difference between states of $180^\circ \pm 2^\circ$, providing 40% bandwidth with in-band insertion loss lower than 2.5 dB and a return loss better than 10 dB. The phase switch provides a $\pm 5^\circ$ phase error in a bandwidth of around 60%, from 18 to 38 GHz.

Introduction: A significant application for wideband phase switches is their use in high-sensitivity receivers for radioastronomy, known as radiometers. Some of these receivers are used to measure the cosmic microwave background (CMB), and several satellite or ground-based projects have been, and are being, developed to perform measurements of this radiation.

Some radiometers are based on differential schemes, such as Dicke [1] or pseudo-correlation [2], where the phase switch circuit is crucial to their performance, since it must introduce a precise 180° phase change between the two states throughout the operating band while providing a constant amplitude response. Large bandwidths are required for these circuits in order to improve radiometer sensitivity [2]. These receivers are made with low-noise amplifiers, hybrid couplers as well as phase switches, and as some of them are used on board, the use of compact modules is required.

Several works [3, 4] have presented phase switches implemented on monolithic microwave integrated circuits (MMIC) using microstrip technology, but for some applications where circuits with large bandwidths are required, the uniplanar technology offers great advantages, avoiding via holes for ground connection and enabling a high level of integration with MMIC chips.

The circuit design is based on the use of a coplanar waveguide (CPW) and a slotline as transmission lines, so transitions from one to the other type of transmission line have been designed, taking into account the work described in several publications [5, 6]. Selecting the appropriate combination of switching elements, the microwave signal travels through different, but symmetrical, paths providing a 180° phase shift. Operation of the phase switching circuit has to allow fast commutation between states, so the choice of the switching device is a significant issue. Experimental results of the phase switch are reported, and the proposed design is validated. Phase difference, return and insertion loss results are compared with different MMIC approaches shown in the literature [3, 4].

Circuit design: The phase switch is based on the use of CPW-to-slotline transitions and a slotline T-junction. The circuit has a CPW input transitioned to slotline, in which the T-junction provides dual transmission paths. The choice of the transmission path, in order to differentiate the signal phase, is made using microwave *pin* diodes, a commonly used component in control applications.

CPW-to-slotline transition design is significant in order to provide wideband operation of the phase switch circuit at millimetre-wave frequencies. The selected topology is shown in Figs. 1*a* and *b*. The design of the transition, in terms of return and insertion loss, was done using an electromagnetic simulator. The transition was designed to match the even-mode of CPW transmission line to slotline mode. To achieve this approach, the side grounds of the CPW line were connected, using gold wire bonding, to ensure the equipotential voltage. The selected impedance of the CPW transmission line was 50 Ω, while slotline impedance had a different value, the 50 Ω gap in the slotline is too narrow for the substrate used. To facilitate implementation in the slotline, several back-to-back CPW to slotline transitions were designed and tested, modifying the slotline gap. These preliminary designs allowed us to evaluate different impedances and choose the most suitable one.

The output CPW-to-slotline transition is a novel design based on the input transition topology. The approach is to achieve a 180° phase difference when the signal is applied to the output transition, exciting the CPW even-mode through one of the two transmission paths. In order to make these dual transmission paths, a T-junction was added in the slotline. The selection of the desired path was done using *pin* diodes. Two anti-parallel diodes were connected to the edges of the T-junction, and another two diodes were placed on the output slotline-to-CPW transition. The diodes in each slotline path are separated by one quarter-wavelength. The position of the diodes can be seen in Fig. 1*c*. The diode configuration uses a pair of them in forward biasing (low impedance), while the other two are simultaneously in reverse biasing (high impedance). Therefore, the transmission path is chosen changing a control DC bias signal. The second diode in the slotline with forward voltage is part of the output transition. Its low resistance is used to make a quarter-wavelength stub in the slotline to readapt slotline mode to CPW even-mode.

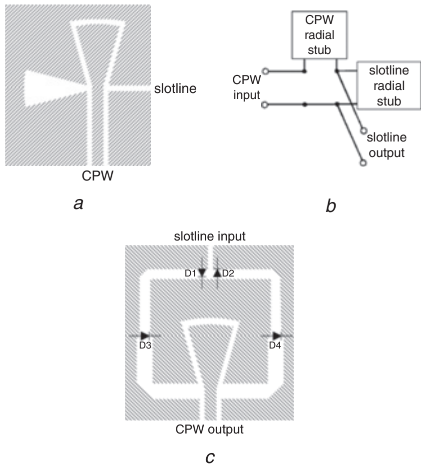

Fig. 1 *Designed CPW-to-slotline transition*

a Circuit layout
b Equivalent circuit schematic
c pin diode connection at T-junction in slotline and output slotline to CPW transition: D1/D3 and D2/D4 in anti-parallel assembly

In order to improve return loss, two different impedance slotline sections were included in the output path, working as wideband matching networks. Thus, the output transition was defined for a different slotline gap. Another feature of this transition was the stub used; the output design was implemented using a standard stub, instead of the radial one in the input CPW to slotline transition.

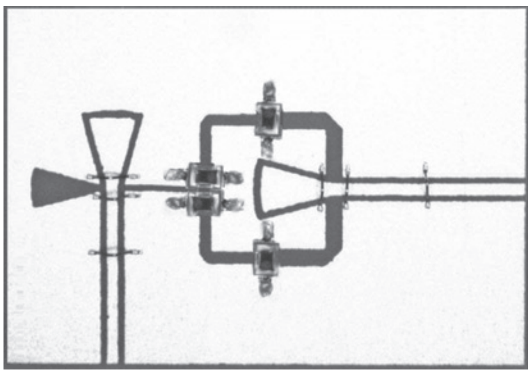

Fig. 2 *Phase switch circuit on alumina*

Implementation and measurement: The phase switch circuit has been manufactured on an alumina substrate ($h = 0.254$ mm, $\varepsilon_r = 9.9$), with 3 μm-thick electroplated gold metallisation. Fig. 2 shows the implemented circuit. As the phase switch uses CPW and slotline topologies, the substrate will just have gold metallisation on the top side, where the circuit is etched, and there is no bottom metallisation. The distance between the bottom side of the alumina substrate and the ground plane underneath is a significant issue. A short distance can make the slot mode degenerate. In order to facilitate the measurement of the circuit, with coplanar probes, an additional substrate was used. This substrate has to present a low relative permittivity, close to the relative permittivity of air. This enables the CPW and slotline transmission lines to behave properly, without a ground plane in the bottom side of the alumina substrate. Thus beneath the alumina, a single-sided copper FoamClad® was used, with $h = 2.59$ mm and $\epsilon_r = 1.18$. The side of the substrate without metallisation has an adhesive layer, where the alumina substrate was placed in order to test the circuit.

The *pin* diodes must have a low junction capacitance and low resistance, in order to minimise their effect on the circuit behaviour. Low capacitance makes the *pin* diode have a good open-circuit effect, and low resistance provides a good short-circuit effect. The combination of the 'open-circuit' and 'short-circuit' diodes guide the signal through a path to the output transition. These features are available in commercial beam-lead *pin* diodes. The chosen one was HPND-4005 from Agilent. This device typically has a 0.017 pF capacitance in reverse bias and 4 Ω resistance in forward bias.

To measure the circuit, a coplanar probe station, stable in-phase coaxial cables from Gore™ and high-performance microwave probes from PicoProbe® were used. In order to supply the circuit, a 200 μm pitch DC probe from Cascade Microtech was used. The DC biasing was done by placing the probe between the borders of the gap in the slotline, and a series resistor was added to protect the diodes.

Experimental results: In order to validate the design, the circuit was measured using a PNA E8364A vector network analyser. Before testing the whole circuit with *pin* diodes, the phase switch was measured by replacing each forward biased *pin* diode with a bonding wire, so two identical designs have been implemented to emulate each state. Once the diodes were assembled, the DC probe was used to supply the set of diodes. To obtain the phase difference, the diode bias voltage was changed from positive to negative. The supply voltage was ±3.2 V, with a total current consumption of 40 mA.

Measurements of return loss, insertion loss and phase difference between states are shown in Fig. 3. A precise phase difference was obtained over the frequency band from 24 to 37 GHz, with a phase error lower than ±2°, a return loss better than 10 dB and an insertion loss lower than 2.5 dB over the band. Amplitude error between states was less than 0.5 dB, and it was due to small physical differences in the transmission paths originating from the fabrication process. Considering a phase error of ±5°, the circuit covered the frequency band from 18 to 38 GHz (65% bandwidth).

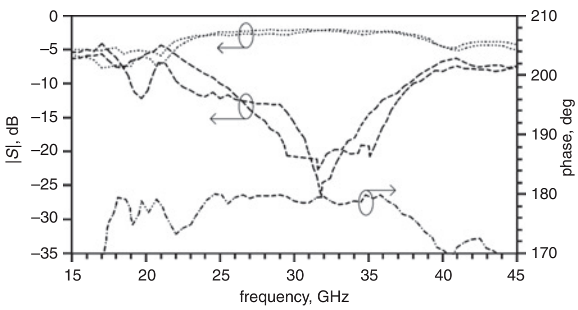

Fig. 3 *Measured phase difference, input return and insertion loss for both states*

Phase difference in dot dashed line (right axis), return loss in dashed line and insertion loss in dotted line (left axis)

Results improve the operation bandwidth and return loss shown in [3] with an error in-phase of ±2°, and with a similar insertion loss. Compared with [4], the phase difference and insertion loss obtained are better over a wider band. In these comparisons, it should be taken into account that both [3] and [4] are MMIC designs whilst this work reports a hybrid design.

Conclusions: A planar Ka-band 180° phase switch design, implementation and measurements have been presented. The design was implemented in a low-cost technology, with a fast manufacturing process. Test results validate the use of the commercial *pin* diode, HPND-4005, as a switching device. The circuit covered the frequency band from 24 to 37 GHz, with an average insertion loss and return loss of 2.2 ± 0.3 and 16 dB, respectively, and with an amplitude balance between states of less than 0.5 dB. The average phase difference was 179.1° ± 0.8° over this frequency band.

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