Broadband Ka-band 90° phase switch for radio astronomy

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

A broadband 90° phase switch based on microstrip bandpass filters (BPFs) is presented. The phase shift expression is derived from the theoretical analysis of π-network BPFs. The broadband behaviour is performed and validated in the Ka-band focused on radioastronomy applications. The commutation between networks is achieved by a single-pole double-throw switch with negligible power consumption. Measured results show an average phase shift of 88° ± 6° in the frequency band from 24 to 37 GHz (more than 42% relative bandwidth), with an amplitude imbalance of around 0.5 dB. The return loss is better than 15 dB. Experimental results demonstrate its suitability to be used in broadband radio astronomy receivers.

Introduction: The design of wideband phase shifting networks has been widely described in the literature [1–6], using quite different topologies. Since Schiffman [5] designed λ/4 coupled-line sections achieving 90° phase shift in a wideband frequency range, many approaches based on loaded transmission lines or bandpass filters related to a reference transmission line have been implemented to improve the operating bandwidth or phase imbalance. Reported results show ultra-wideband behaviour in low-frequency bands (up to 15 GHz), mostly, without the integration of switching device between branches [1–5].

This Letter proposes a 90° phase switch circuit working in Ka-band, including the switching device. The design is focused on covering the frequency band from 26 to 36 GHz, with the aim of being used in QUIJOTE Phase II radio astronomy receivers to characterise the CMB polarisation [7]. The receiver comprises 90° phase switches to generate polarisation states and their performance is crucial in order to overcome the 1/f noise and different systematic errors in the receiver. They must introduce an accurate 90° phase change across the operating band, whilst maintaining a constant amplitude response.

The phase switch is based on using two broadband distributed π-networks to obtain a 90° differential phase. Both networks act as low-loss, well-balanced wideband filters. The commutation is performed by a single-pole double-throw (SPDT) monolithic microwave integrated circuit (MMIC) switch. The integration and characterisation of broadband branches with a switching device at millimetre-wave frequencies are shown, obtaining a wideband phase difference response.

Phase switch design: The configuration of the phase switch circuit is depicted in Fig. 1, where Z_i ($i = 0,\ldots,2$) are the impedances and Φ_j ($j = 1,\ldots,5$) and Φ_{stubk} ($k = 1,\ldots,4$) the electrical lengths of the lines. The insertion loss of both networks must be very well balanced with a minimum phase error in the whole frequency band.

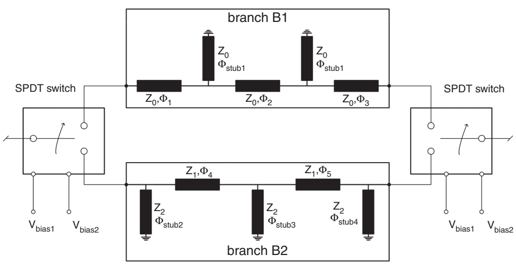

Fig. 1 *Phase switch circuit topology: SPDT switches and 90° phase difference BPF networks (Z_0 = 50 Ω)*

Two SPDT switches are used to select the propagation network in each state, depending on two DC bias signals. The switches must have excellent return loss and good isolation in order to minimise in-band ripple and avoid non-desired coupling to the switched-out branch.

A. Broadband network design: To obtain broadband behaviour and simultaneously minimise the phase and amplitude errors, two different interrelated networks (BPFs) were designed, with a minimum amplitude imbalance and covering a relative bandwidth larger than 30%. Basic BPF theory for the design of stub-based filters is well-known and described in [8] for wideband responses, through the lowpass to bandpass mapping used to determine the number of sections, ripple and attenuation.

Analysing the BPFs as π-networks, their admittance matrixes are easily obtained, so the phase dependence at the centre frequency f_0 can be expressed as in (1):

$$\begin{aligned}
\Delta\phi(f_0) &= \phi_{B1}(f_0) - \phi_{B2}(f_0) \\
\phi_{B1}(f_0) &= \Phi_1 + \cos^{-1}\left[\frac{\sin(\Phi_{stub1} + \Phi_2)}{\sin(\Phi_{stub1})}\right] + \Phi_3 \\
\phi_{B2}(f_0) &= \cos^{-1}\left[\frac{Y_2}{Y_1}\cot(\Phi_{stub2})\sin(\Phi_4) + \cos(\Phi_4)\right] \\
&\quad + \cos^{-1}\left[\frac{Y_2}{Y_1}\cot(\Phi_{stub4})\sin(\Phi_5) + \cos(\Phi_5)\right]
\end{aligned} \tag{1}$$

where Y_i are the admittances defined by $1/Z_i$.

The parameters in branch B2, electrical lengths Φ_{sutb2}, Φ_{sutb3} and Φ_{sutb4}, and impedances Z_1 and Z_2, are calculated in order to get a requested phase difference from branch B1. Its topology can be analysed as two cascaded π-networks, where the centre stub (Φ_{sutb3}) is equivalent to two equal impedance parallel stubs with electrical lengths Φ_{sutb2} and Φ_{sutb4}. The equivalent electrical length of this centre stub at f_0 is defined in (2):

$$\Phi_{stub3} = \cot^{-1}(\cot(\Phi_{stub2}) + \cot(\Phi_{stub4})) \tag{2}$$

The BPFs are implemented in microstrip technology, and T-junctions to connect the transmission lines are considered, since their effect is quite relevant at Ka-band. Therefore, the electrical lengths of the lines are slightly modified from the theoretical approach, in order to get a trade-off between return loss and phase-amplitude imbalances. The designs were aided with electromagnetic simulators.

B. SPDT switch: The device used to switch between phase shifting branches is an MMIC SPDT based on a pseudomorphic HEMT. The AMMC-2008 device from Avago Technologies is selected for its return loss level, high isolation between outputs, and its negligible power consumption due to its pseudomorphic HEMT (pHEMT) technology faced *pin* diode solutions. This SPDT has an attenuation of around 2 dB in its transmitted branch, with an isolation of around 30 dB at 31 GHz.

Experimental results: Both branches were manufactured on a Teflon-based substrate (5 mils CLTE-XT from Arlon). The implemented parameters were Z_1 = 48 Ω, Z_2 = 52 Ω, Φ_1 = 105°, Φ_2 = 83°, Φ_3 = 64°, Φ_4 = 97°, Φ_5 = 93°, Φ_{stub1} = 89°, Φ_{stub2} = 70°, Φ_{stub3} = 53° and Φ_{stub4} = 65° at f_0 = 31 GHz. Coplanar waveguide-to-microstrip transitions were used to characterise the circuits on a coplanar probe station. Results for phase difference and amplitude imbalance are depicted in Fig. 2. From measurements, an average phase shift of 89° ± 4° is obtained between branches over the 24–37 GHz band, with an amplitude imbalance of around 0.1 dB.

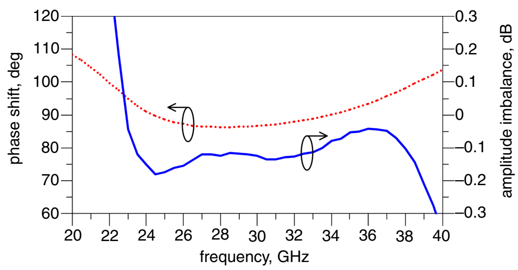

Fig. 2 *Measured amplitude imbalance (solid line) and phase shift (dotted line) between BPF branches*

The circuit assembly including the SPDT MMICs is shown in Fig. 3. The bias circuit for switches includes 100 pF capacitors. Two switching DC signals (0 and − 3 V, respectively) were applied. The phase switch was characterised in a coplanar probe station directly on SPDT accesses. Its measured results are depicted in Figs. 4 and 5. An average phase shift of 88° ± 6° was measured in the band from 24 to 37 GHz, with insertion loss of about 4.5 dB. Input return loss is better than 15 dB in the whole interest band.

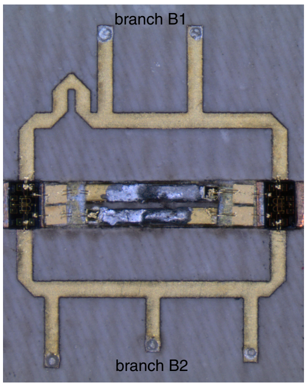

Fig. 3 *Circuit assembly with MMIC SPDT switches and microstrip branches*

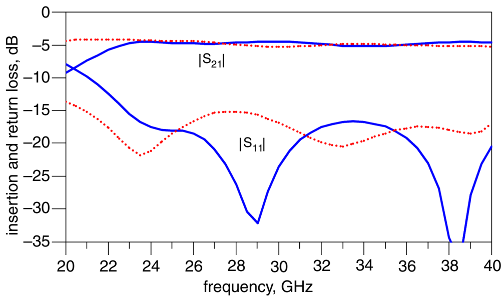

Fig. 4 *Insertion and input return loss of phase switch in each state*
a $V_{bias1} = 0$ V, $V_{bias2} = -3$ V state (solid line)
b $V_{bias1} = -3$ V, $V_{bias2} = 0$ V state (dotted line)

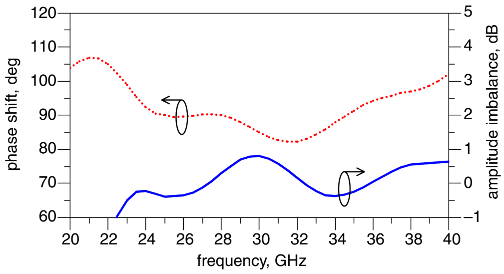

Fig. 5 *Tested amplitude imbalance (solid line) and phase shift (dotted line) of phase switch*

An increase in the measured ripple is observed regarding individually tested branches, due to the differences of bonding wire length connections between both SPDTs and microstrip branches at circuit accesses, which are very critical at these frequencies. The presented Ka-band 90° phase switch has demonstrated an outstanding performance over a wide frequency band, and with the main advantage of featuring an integrated switch function compared to previous published work [1–5].

Conclusion: The design, full integration and characterisation of a broadband Ka-band 90° phase switch are described. Two wideband branches using π-topology in microstrip lines were designed. A SPDT MMIC based on PHEMT technology was used to switch between the designed branches. Results show an average phase shift of 88° ± 6° over the frequency band of 24–37 GHz (more than 42% relative bandwidth), an amplitude imbalance of less than 0.5 dB and return losses better than 15 dB, with negligible power consumption.

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One or more of the Figures in this Letter are available in colour online.

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