Broadband Liquid Crystal Based Reflection-type Phase Shifter in 60 GHz Band

S. Bulja[1], D. Mirshekar-Syahkal[2], M. Yazdanpanahi[2], R. James[3], S. E. Day[3] and F. A. Fernandez[3]
[1]Bell Labs, Alcatel-Lucent, Dublin 15, Ireland. [1]email: senad.bulja@alcatel-lucent.com
[2]School of Computer Science and Electronic Engineering, University of Essex, Colchester, Essex, CO4 3SQ, U.K.
[2]email: {dariush, myazda}@essex.ac.uk
[3]Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, U.K.
[3]email: {r.james, s.day, a.fernandez}@ee.ucl.ac.uk

Abstract

A mm-wave broadband microstrip reflection-type phase shifter (RTPS) based on nematic liquid crystal (LC) is presented. It consists of a broadband 3-dB coupler and broadband tunable reflective loads based on a nematic LC substrate. The nematic LC used as the substrate is E7, available commercially.

Keywords: Dielectric anisotropy, liquid crystal (LC), reflection-type phase shifter (RTPS).

1. Introduction

The interest in the mm-wave band has created new opportunities for the development of a variety of RF devices which will eventually become part of mm-wave communication systems [1]. These devices will be preferably reconfigurable, ultra-compact and cost effective.

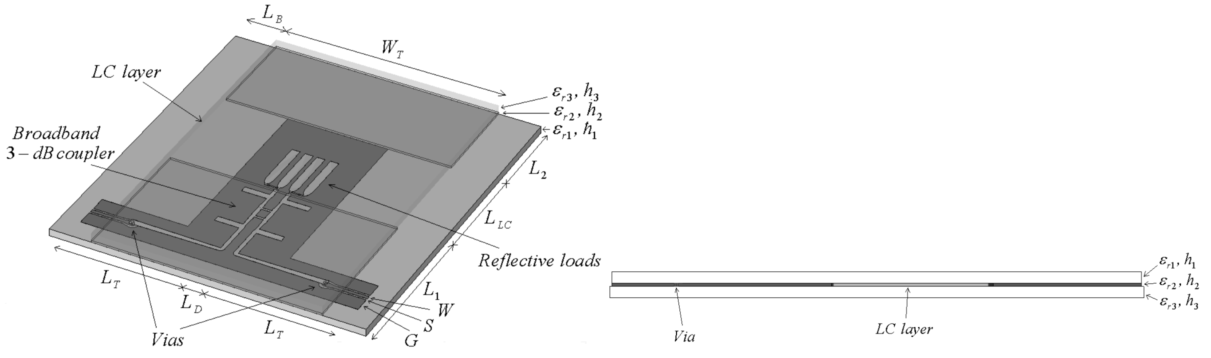
Nematic liquid crystal (LC) materials possess a birefringence that extends into the mm-wave range [2]. Low voltages can be used to control this birefringence, making these materials attractive for the development of a variety of mm-wave reconfigurable devices. Various LC based mm-wave devices have already been reported in the literature, such as phase shifters [3] and voltage tuned antennas [4]. In [3], the phase shifter is simply a length of a microstrip line, exposed to an LC substrate. The amount of phase shift obtainable from such phase shifters is limited and directly proportional to the length of the microstrip line. This becomes highly impractical due to large device circuit size when a high value of phase shift is needed.

The LC based RTPS was first introduced in [5] and achieved a maximum phase shift of about $130°$ and a figure-of-merit of $11.4°/dB$ around 61 GHz. A distinctive feature of this phase shifter lies in its small circuit size of 3.4 x 6.2 mm^2. This was a significant size reduction when compared to the LC based microstrip line phase shifter of [3]. The response of the LC based RTPS in [5] is then further refined in [6]. In both of these phase shifters an LC nematic mixture, E7, was used as a dielectric tuneable material in the circuit of the reflective loads.

In this paper, a new broadband LC based RTPS is presented, improving on some of the shortcomings of the LC based RTPS reported in [5]-[6]; i.e. low figures-of-merit, small bandwidth and relatively low phase shift. Its circuit size is slightly increased, as a broadband 3-dB coupler and reflective loads are accommodated in its structure. In its present experimental form, it has a circuit footprint of 9.74 x 5.3 mm^2. In order to provide direct comparison with RTPSs in [5] and [6], the same LC mixture, E7, was also used as a tuneable dielectric substrate in this work.

2. Broadband LC Based RTPS Design

The physical structure of the broadband LC-based RTPS is shown in Fig. 1. The RTPS consists of two LC exposed reflective loads, a broadband coupler and two CPW-microstrip transitions. The transitions are necessary for low frequency biasing and for correct interfaces to coplanar probes used in measurements. The length of each transition is $L_T = 6.93\,mm$. The proposed RTPS is a three layer structure and the dielectric constants and thicknesses of each layer are:



(a) (b)

Fig.1. Structure of broadband LC based RTPS at 60 GHz; (a) perspective view and (b) side view

$\varepsilon_{r1}=9.8$, $h_1=381\mu m$, $\varepsilon_{r2}=3.66$, $h_2=101\mu m$, $\varepsilon_{r3}=3.27$ and $h_3=381\mu m$. In this particular design, the CPW section of the transitions is printed on the top side of the bottom layer, which has a high dielectric constant, $\varepsilon_{r1}=9.8$, needed to achieve a characteristic impedance of 50Ω for a practically realizable spacing, S , between the centre conductor and the ground planes. The dimensions of the CPW of Fig. 1 are: $G=810\mu m$, $S=90\mu m$ and $W=200\mu m$. The other dimensions in Fig. 1 are: $L_1=7.56mm$, $L_2=5.15mm$, $L_B=2.21mm$, $L_D=0.48mm$ $L_{LC}=5.46mm$ and $W_T=11.9mm$. The centre conductor of the CPW is connected through a buried via in the middle substrate to the microstrip line printed on the bottom side of the top layer, effectively forming the CPW-microstrip transition. This transition is broadband and its -10 dB bandwidth covers the range from DC to 67 GHz.

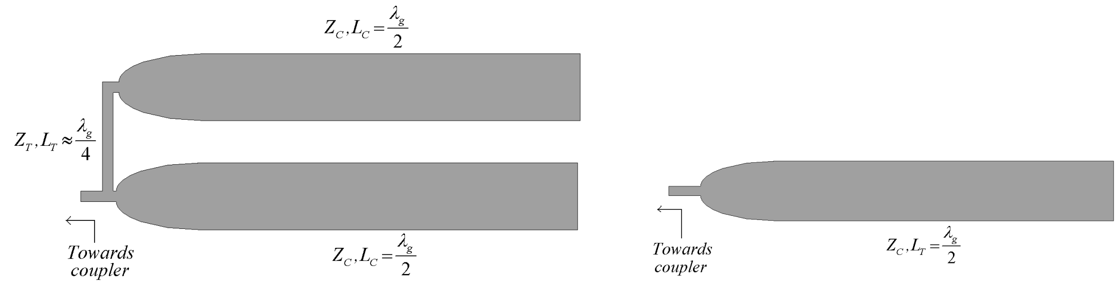
The 3-dB broadband coupler was designed using equations in [7]. Its simulated bandwidth, with 1 dB amplitude imbalance in the direct and coupled arms ranges from 53 GHz to 70 GHz, while the -10 dB return loss bandwidth ranged from 48 GHz to 69 GHz.

The structure of the broadband reflective loads is given in Fig. 2.a. It comprises two slightly tapered half-wavelength microstrip lines connected in parallel through a quarter wave transformer with a characteristic impedance of Z_T . Tapering is used to minimize the reflections at the boundaries between the reflective loads and the coupler as well as to increase the phase shift bandwidth.

It is shown in [8] that the connection of two reflective loads, through a quarter-wave transformer, Fig. 2.a, leads to an increase in the resulting phase shift. The increase is a function of the characteristic impedance of the quarter-wave transformer. In this work, the characteristic impedance of the transformer is set to $Z_T \approx 90\Omega$, while the characteristic impedance of the LC exposed loads is $Z_C=30\Omega$.

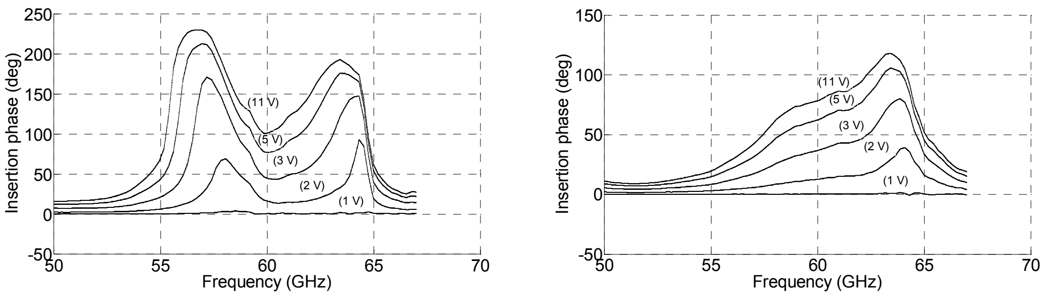
3. Measured Results

For the purpose of the measurements, two phase shifters were fabricated. The first phase shifter is the RTPS of Fig. 1 using the broadband reflective loads of Fig. 2.a. The second phase shifter is a narrowband RTPS and it consists of the same circuit as the broadband RTPS, with the



(a) (b)

Fig.2 Reflective loads (a) broadband and (b) narrowband



(a) (b)

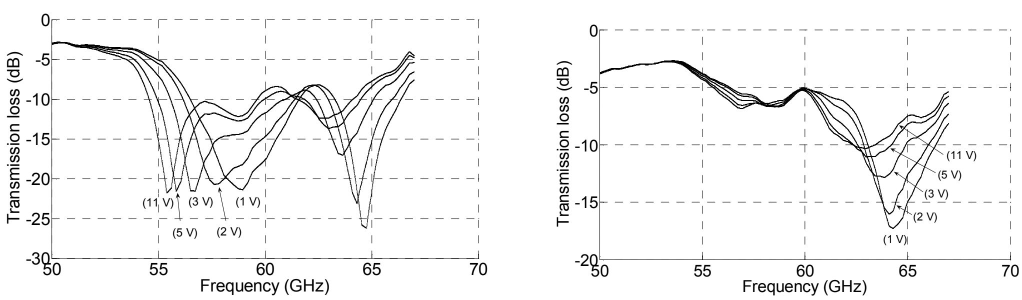
Fig. 3 Measured differential phase shift (relative to 0 V) for different voltages of a) broadband RTPS and b) narrowband RTPS

exception of the reflective loads which are narrowband, Fig. 2.b. Each layer of the RTPSs of Fig. 1 was fabricated using a standard photolithography process on Rogers substrates [9]. After patterning, the electrodes (forming the reflective loads) and the ground plane are covered with a thin layer of polyimide and then mechanically rubbed with a rubbing cloth. This process is needed for anchoring and the alignment of the LC molecules, defining the so-called "ground state" or "switched off state" of the LC in the absence of applied bias voltage. The three layers are bonded together using an epoxy and in the cavity formed, Fig. 1, the LC mixture, E7 is injected. In the frequency range of interest (50 – 67 GHz), the dielectric constant of E7 along a direction perpendicular to the LC directors is $\varepsilon_{r\perp}=2.72$ and along a direction parallel to the directors is $\varepsilon_{r\parallel}=3.18$ [2].

In the measurements, a slow varying ac voltage ($\sim 200\,Hz$) is applied through a wideband bias tee to the CPW terminals of the RTPSs. The peak bias voltage is then varied from 0 V (switched off state) to 11 V (switched on state), and the overall S-parameters of each RTPS are measured at each selected voltage. The measured S-parameters of the CPW-microstrip transition, obtained using the TL method of [10], are then subtracted from the measured overall S-parameters of the RTPSs to obtain the actual performance of the two RTPSs.

The measured (differential) phase shifts of the transmission coefficient $|S_{21}|$ of the two RTPSs at bias voltages of 1 V, 2 V, 3 V, 5 V and 11 V relative to 0 V are presented in Fig. 3. The maximum phase shift occurs at a bias voltage of 11 V, which corresponds to the fully switched on state. The insertion losses of the two phase shifters are shown in Fig. 4. The return losses of both phase shifters are generally below -10 dB for a range of operating frequencies covering 60 GHz. As seen in Fig. 3, the broadband phase shifter has a double peak in its phase shift performance over the broad frequency range of 55.5 - 64.5 GHz. By changing the length of the reflected loads, these two peaks can be brought in closer. It is evident from Figs. 3-4 that both RTPSs suffer from relatively high insertion losses. The main causes can be the unbalanced reflective loads, conductor and the LC losses. Improving the fabrication process and choosing an appropriate LC for RF applications can reduce the losses.

The performance of a phase shifter is normally gauged by its Figure-of-Merit (FoM), defined as the ratio of the maximum phase shift to its associated insertion loss. The FoMs of the two



a) (b)

Fig. 4 Measured insertion losses at different voltages of a) broadband RTPS and b) narrowband RTPS

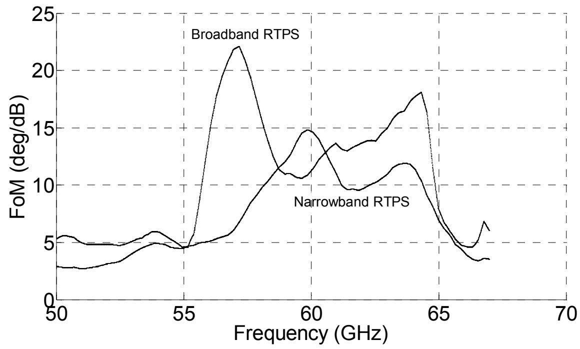


Fig. 5 Measured figures-of-merit of broadband and narrowband RTPSs

RTPSs are presented in Fig. 5, from which it can be inferred that the broadband RTPS has a conclusive edge over it narrowband counterpart. For example, the broadband RTPS experiences a broader phase shift bandwidth and higher FoMs. In particular, the FoM of $22° / dB$ achieved by the broadband RTPS is the highest FoM achieved using the E7 LC mixture.

4. Conclusion

A broadband reflection-type phase shifter (RTPS) based on liquid crystals (LC) is presented in this paper. The measurements showed that it achieves its best figure of merit of $22° / dB$ at 57 GHz, coinciding with a maximum differential phase shift of $230°$. Its circuit size is 9.74 x 5.3 mm^2.

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