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RESEARCH PAPER

Reliability study of a tunable Ka-band SIW-phase shifter based on liquid crystal in LTCC-technology

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A tunable substrate-integrated waveguide phase shifter using low-temperature co-fired ceramic (LTCC)-technology is presented in this paper. By changing the effective permittivity in the liquid crystal (LC)-filled waveguide, the differential phase can be tuned continuously. This is achieved by means of an analog signal applied to the electrodes, surrounding the LC. The design allows for precise tuning of the differential phase, which is proven with a Monte Carlo measurement resulting in phase errors of less than 3° at 28 GHz. Besides that, the ambient temperature dependency of the module is shown. The phase shifter has a high integration level and can be included into a complete and lightweight single-phased array antenna module. The phase shifter is realized with a high level of integration which is available through the multilayer process of the LTCC. It has a length of 50 and provides a differential phase shift of more than 360° at 28 GHz. The figure of merit for tunable phase shifters is >40°/dB.

Keywords: Passive components and circuits, New and emerging technologies and materials

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I. INTRODUCTION

During the past decade, the technology of phased arrays has taken up a great demand. When it comes to mobile participants, high gain paired with a steerable antenna beam is of great value. Thus, there is a demand for tunable microwave components such as phase shifters, which can be realized by different technologies such as micro electro mechanical systems (MEMS) [1, 2] or monolithic microwave integrated circuit (MMIC) [3]. Another option is tunable dielectrics such as ferroelectrics [4, 5] and liquid crystal (LC) [6, 7]. LC has been in the focus of microwave engineers of more than 20 years [6]. Since then, its dielectric anisotropy has been increased for usage in microwave components while decreasing the dielectric loss significantly [7]. Besides the material improvements, a lot of continuous tunable components such as varactors [8], phase shifters [6], and polarizers [9] with LC have been investigated.

Components using LC provides several challenges. The LC is a liquid, which needs to be sealed into a proper reservoir. Also, a biasing structure is integrated into the structure, so the LC can be steered through an electric field. Both challenges can be solved using the low-temperature co-fired ceramic (LTCC), which allows integration of microwave components, cavities, and DC biasing network, using a multilayer approach [10]. Earlier work describes the LTCC-integrated tunable phase shifter with LC [11, 12]. As an improvement in the work done before, the work presented here aims toward improved tuning speed and a higher tunability of the transmission line phase shifters. The phase shifter is part of a 4 × 1 phased array antenna module, which is stackable to a larger array, and has been briefly introduced in [13], where *S*-Parameters and switching time measurements are presented.

In this paper, we present a detailed view of the design and the characterization of the substrate-integrated waveguide (SIW)-LTCC phase shifter. The fundamentals of LC are briefly explained in Section II, advancing to the design of the phase shifter in Section III. Eventually, the measurement results of the temperature dependency as well as repeatability studies are shown in Section IV.

II. LIQUID CRYSTAL

LC is a dielectric material, which has, in between the solid and liquid states, several mesomorphic phases [14]. The mesomorphic phase used here is the nematic phase. In the

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common liquid state, the material is isotropic, whereas in the nematic phase, the rod-shaped LC molecules have orientational order, which leads to an anisotropic behavior. Besides that the LC flows like a liquid and its orientation can be directed through an electric or magnetic field, where the LC aligns along the biasing-field vectors. The longer axis, which in this case has a higher permittivity, is named the parallel (‖, Fig. 1(a)) alignment, whereas the lower permittivities are called perpendicular (⊥, Fig. 1(c)). This allows for electromagnetic devices to tune the effective permittivity of a radio-frequency (RF) field as shown in Fig. 1. Using the transmission line approach, this is used to alter the propagation velocity of the wave to get relative phase differences between phase shifters.

The LC mixture TUD-566 is used in this project and has permittivity values of $\varepsilon_{r,\parallel} \approx 3.11$ and $\varepsilon_{r,\perp} \approx 2.32$ at 30 GHz. The corresponding dielectric losses are $\tan\delta_{\parallel} = 0.0021$ and $\tan\delta_{\perp} = 0.0066$ at room temperature. The temperature dependency of TUD-566 is shown in Fig. 2. The clearing point at which TUD-566 becomes isotropic is approximately 115°C.

In many applications as found in the LC-display technology [15, 16], the LCs default orientation is parallel to the surface with metallization such as the ground plane or microstrip lines. When a voltage is applied across the ground and signal electrodes of the microstrip line, the LC changes its orientation toward a parallel orientation with respect to the RF field. When the voltage is turned off, the LC returns to the initial state. The tuned alignment depends on the voltage level, because equilibrium is found between the torque introduced by the biasing field and the elastic force between the LC molecules. For this approach, the LC molecules are to be anchored to the surfaces to ensure the realignment to the default state. In this work, however, the prealignment is omitted and an electric biasing field is used to steer the LC molecules to any direction. Therefore, only the direction of the biasing field is important, whereas the tuning speed of the LC is dependent on the LC viscosity and the applied biasing field strength. This allows for faster tuning, because the realignment does not depend only on the LC material parameters.

III. PHASE SHIFTER

A) Design

A photograph of the phase shifter is shown in Fig. 3. The LTCC-material is CT707 from W.C. Heraeus GmbH with a relative dielectric constant ε_r of 7.1 and $\tan\delta$ of 0.004. The phase shifter is an SIW with a buried cavity for the LC. The LC is used as a tunable dielectric to adjust the propagation velocity of the traveling wave. A characterization of a typical LTCC-SIW is shown in [17].

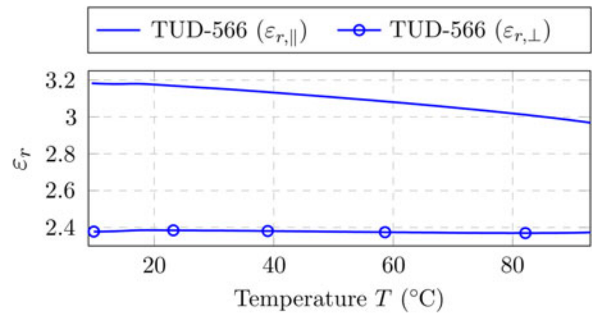

Fig. 2. Relative dielectric constant over temperature of the LC mixture TUD-566.

Besides the electromagnetic requirements, the LTCC has some design rules. Figure 4 shows the multilayer setup. The SIW is made up of two metallization layers for the top and bottom electric walls and via fences for the side walls to connect the layers. The distance between the vias is chosen as the minimum distance available in the given technological process to ensure good electrical shielding. A buried cavity for the LC is in this SIW. As a biasing network for the LC, the floor and the ceiling of the cavity are covered with a line structure of resistive paste with a square resistance of $R_s = 1$ MΩ. The high resistivity is chosen to avoid unwanted coupling of the RF-waveguide mode into microstrip modes.

For characterization "on wafer Ground-Signal-Ground (GSG) probes" are used. Therefore, transitions from grounded coplanar waveguide (GCPW) to stripline and further to the SIW have been designed. The stripline leads into the SIW through a magnetic coupling via as reported in [18].

The cross-section of the phase shifter is shown in Fig. 5(a). One more layer of LTCC has been included in between the upper and lower waveguide boundaries and the cavity. This gives a total stack of ten LTCC layers with a total height of 1.2 mm and a width of 4 mm. Even with the high effective permittivity of the LC, modes of higher order will not propagate in the waveguide. The phase shifter prototype in Fig. 6 has been simulated and optimized using CST Microwave Studio®. The LTCC integrated structures need to be simulated with a three-dimensional simulation tool, due to its inhomogeneous layout.

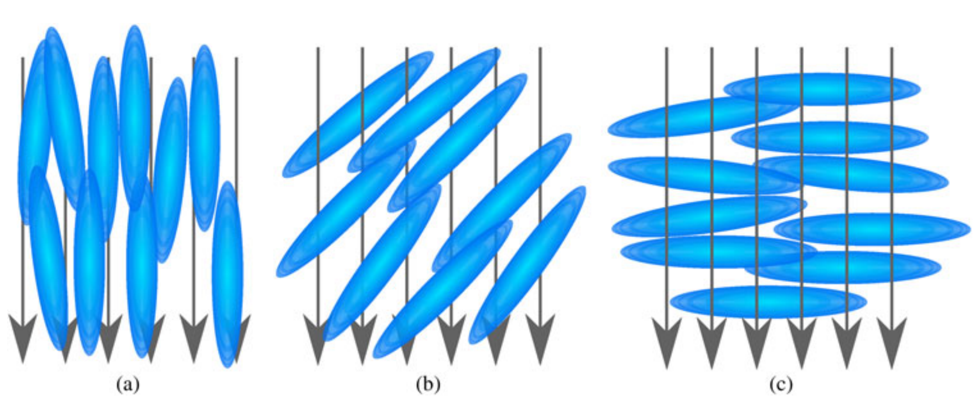

Fig. 1. LC molecule and the effective permittivities for the RF-field vectors.

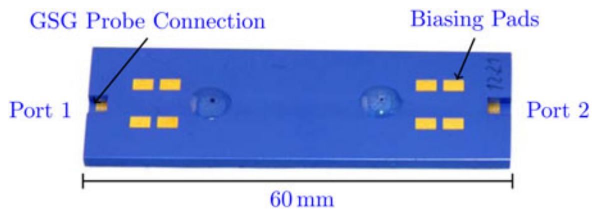

Fig. 3. Schematic drawings of the resistive layers between the electrodes with metal electrodes left and right of the resistive layer.

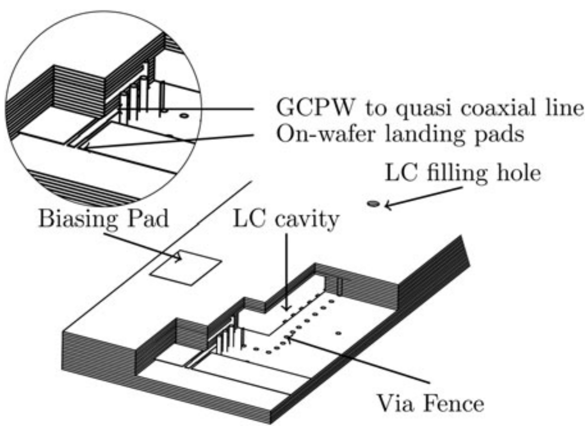

Fig. 4. Wire drawing of the transition part of the phase shifter test module.

The filling hole has a diameter of 0.5 mm. When filling the cavity with LC, a cone is glued on top of the hole and filled with LC. The module is put into a vacuum bell jar with an air pressure of approximately 0.1 Pa, so the LC can fumigate and the air in the cavity evacuates through the LC reservoir. Eventually, when returning the air back into the vacuum bell jar, the LC is pushed into the cavity. The air bubble free filling is verified with an acoustic discharge measurement.

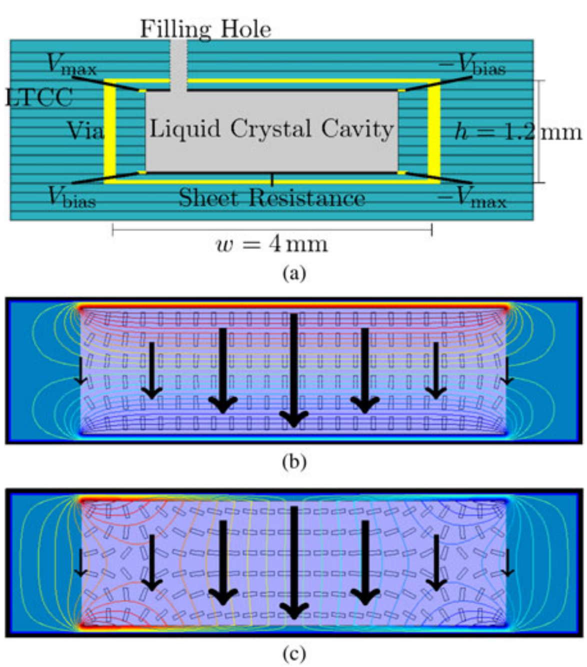

Fig. 5. Cross-section of the phase shifter with DC biasing field distributions and TE_{10}-mode.

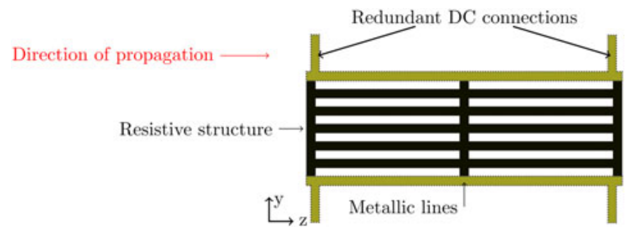

Fig. 6. Photograph of the phase shifter module with ground-signal-ground (GSG) probe connections.

B) Biasing scheme for the LC

The basic biasing scheme in the waveguide cross-section is shown in Fig. 5(a). An electrostatic field, similar to that of a parallel plate capacitor, is induced, when $V_{bias} = V_{max}$, which can be any voltage level that is sufficiently high to align the LC in the desired timeframe. This forces the LC molecules to align in parallel to the RF-field vectors of the TE_{10}-mode as seen in Fig. 5(b). If $V_{bias} = -V_{\max}$, a current flow is induced in the resistive layers and a voltage drop is achieved. This enables the perpendicular alignment as shown in Fig. 5(c). All intermediate levels with $-V_{\max} \leq V_{bias} \leq V_{\max}$ can be applied to steer the effective permittivity in the SIW to the desired value continuously. The phase shifter with its LC-filled part is simulated with an in house two-dimensional (2D) FDFD solver, which includes the orientation of the LC molecules [19]. With these results, an optimization of the biasing field for the LC orientation is possible. The obtained phase constants at 28 GHz are $\beta_{\perp} = 37.7^{\circ}$/mm and $\beta_{\parallel} = 47^{\circ}$/mm, which gives a differential phase constant $\Delta\beta = 9.3^{\circ}$/mm . This results in a minimum length for the phase shifter of 38.7 mm, when assuming the necessary 360° phase shift. The phase shifter length is chosen to be 50 mm.

The biasing takes place with a maximum of 400 V which results in a medium field strength of $E_{\min} = 13.33$ kV/m for the perpendicular alignment as shown in Fig. 5(c). The parallel alignment in Fig. 5(b) benefits from the rectangular structure of the SIW. Therefore, the medium field strength is $E = 40$ kV/m and the tuning into parallel alignment is faster as seen in Section IV.

Because of the ohmic losses within the resistive layers, heating occurs in the cavity. The self heating, which leads to a degredation in tunability, has been discussed in [20]. In that paper, we have shown a phase shifter with a full resistive layer, which had a maximum power dissipation of 1.6 W which leads to a self-heating of the LC and therefore a reduction of phase shift over time. A layout for the resistive layers, which prevents excessive self heating, has been designed as shown in Fig. 3. Most of the power dissipation takes place when biasing the LC to the perpendicular alignment because of the current flow through the resistive layers. Three lines, each with a width of 0.2 mm form the resistivity value, whereas the comb-like structures help distributing the biasing potential along the whole waveguide. The values obtained from several prototypes are in the range from 10.8 to 16 MΩ. The huge variance in the resistivity values is due

Table 1. Comparison of recent electrically tunable liquid crystal phase shifters.

Citation	LC	Topology	Frequency (GHz)	FoM (°/dB)
[23]	E7	Inverted microstrip line	50	20
[24]	TUD-566	Waveguide	30	130
[25]	GT3-23001	CMOS slow wave variable delay line	45	52
[26]	MDA-00-3506	Meandered stripline	60	8.4
This work	TUD-566	SIW	28	41

to uncertainties with the buried layers in the LTCC process [21].

IV. MEASUREMENT RESULTS

The final modules were then filled with LC and characterized using the VNA 37397c from Anritsu. Besides the spectral characterization to investigate the transmission and reflection of the device, the switching times over temperature are measured with a continuous wave excitation. This allows for a better physical understanding of the device when looking at real-life scenarios.

To compare different passive phase shifter technologies, a frequency-dependent figure of merit (FoM) as defined in [22] has been used:

$$FoM = \frac{\Delta\Phi_{max}}{IL_{max}}. \qquad (1)$$

The FoM values for the phase shifter are moderate but due to the high perpendicular losses and the LTCC-substrate not in the region of other LC-phase shifters, which reach an FoM of more than 100°/dB (see Table 1).

A) Temperature dependencies

The temperature dependency of the LC (shown in Fig. 2) also influences the maximum differential phase shift. The investigation has been carried out with a hot plate to increase the ambient temperature step by step. This gives, as seen in Fig. 7, the maximum phase shift as well as the switching time, which decreases due to a lower viscosity of the LC when heating up. The clearing point of the LC is 115°C, so the 120°C curve shows a non-tunable system behavior. When looking at the characteristics shown in Fig. 2, the results are in good agreement with the material characteristics. The differential phase shift drops from the initial 360° at room temperature to about 310° at 80°C.

As one can see in the voltage to phase shift characteristic (Fig. 8(a)), the maximum differential phase shift dropped from 400° to about 360°. This is because of leakage due to expansion of the LC after heating up. Nevertheless, the effect on the differential phase shift after increasing the temperature is still valid, especially when looking at difference.

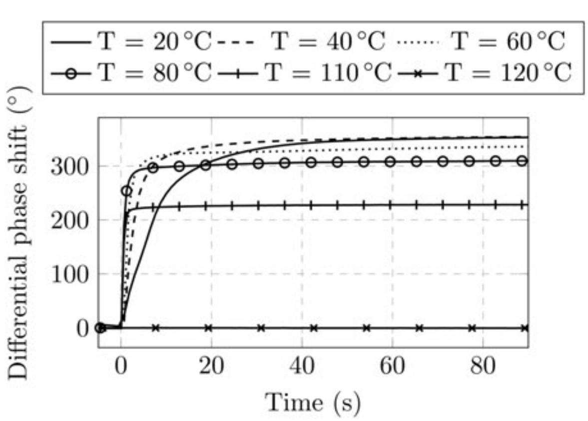

Fig. 7. Differential phase shift over time with different ambient temperature values up to the clearing point of the LC at 28 GHz with V_{bias} switched between −200 and 200 V.

B) Voltage to differential phase shift

The characterization of the differential phase shift over the applied biasing voltage V_{bias} is essential for the operation of the phase shifter. These curves are obtained by applying a voltage V_{bias} and after a settling time of 10 min, the *S*-parameters are recorded. The graph in Fig. 8(a) shows the curve for 28 GHz. The result lead to a $\Delta\beta_{meas} = 7.9°/mm$, which is less than the value of $\Delta\beta_{sim} = 9.3°/mm$ obtained through the previously mentioned 2D mode calculation. There are several reasons for that. The biasing scheme from the 2D simulation does not take the line structure from Fig. 3 into account. Since the LTCC is sintered under pressure, the cavity is reduced in height, especially in the middle, which can lead to a waveguide with less height and therefore less LC.

The measurement based on the Monte Carlo method show a repeatability study, which for the first time, shows the reliability of an LC phase shifter. During these measurements, a random biasing voltage is applied to the biasing network. The measurement is taken as the correct characteristic for this study. The *S*-parameters are either recorded after a maximum time of 5 min or if the results are within a predefined phase of 3°. The graph in Fig. 8(b) shows the measurement results. It shows clearly that the phase deviation is increased with higher differential bias voltage and the overall deviation is reduced for smaller changes. These

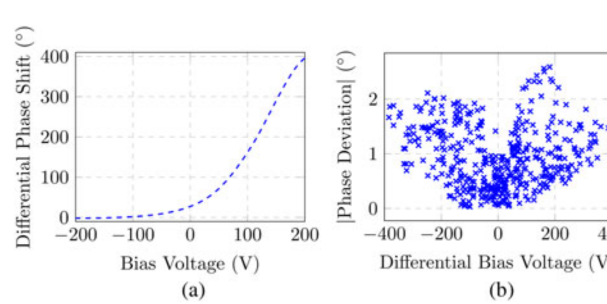

Fig. 8. Voltage to differential phase shift and Monte Carlo measurement.

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measurements were taken in a temperature controlled environment at room temperature.

V. CONCLUSION

A phase shifter for beam-tracking applications has been implemented and analyzed intensively. The embedded SIW transmission line phase shifter provides a differential phase shift of 400° at 28 GHz. The integration level of LTCC allows an easy implementation of cavities for the LC along with all the lines required to build easily implementable phased arrays. The analog steering gives a high repeatability regarding the phase shift with an absolute error margin of maximum 3°.

Because of the tuning time the phase shifter is mostly suited for array applications, which do not go for space division multiple accesses but rather for slowly adjusting the direction of the main lobe. Investigations as in [27] of arrays with slow phase shifters show, that the steering can be about three times faster than the single phase shifter. The LC has a temperature dependency, which needs to be considered when designing a phased array. This behavior can either be countered using a temperature measurement to include into the voltage selection or the implementation of a full control loop using phase measurement.

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Alexander Gaebler was born in Cottbus, Germany, in 1977. He received his Dipl. Ing. degree in Electrical Engineering and B.S. degree in Information and Media Technique from the Brandenburgische Technische Universitaet Cottbus, Cottbus, Germany in 2005 and 2006, respectively. He finished his Ph.D. degree in 2013.

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Torsten Rabe was born in Fuerstenberg, Germany, in 1957. He received his Dipl.-Ing. and Ph.D. degrees in Material Science at Bauhaus University in Weimar/Germany, in 1980 and 1983, respectively. In 1983, he joined Division Ceramic Materials at Academy of Sciences in Berlin. Since 1991, he has been working in the Division Advanced Technical Ceramics at the German Federal Institute for Materials Research and Testing (BAM). He is the head of the laboratory Functional Ceramics and Multilayer Technology. The main focus of his research activities is material development (LTCC and HTCC), tape casting, multilayer technology, brazing of ceramic materials, and non-destructive testing of green and sintered ceramic components.

Ruediger Follmann studied Electrical Engineering at the RWTH Aachen, Germany. In 1994, he joined IMST, where he worked on non-linear device characterization and modeling. After receiving his Ph.D. in 1998 from the University Duisburg, Germany, he became head of the section MMIC design at the IMST, where he developed several sensor and radar components. Since 2002, he has been head of the section RF components. The main focus of the section is set to integrated high-frequency components and chip sets based upon different material systems. Since 2012, Dr. Follmann has been the "Director Integrated Solutions".

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