# Tunable Inverted-Microstrip Phase Shifter Device Using Nematic Liquid Crystals

Carsten Weil [1], Georg Luessem [2], and Rolf Jakoby [1]

[1] Institut für Hochfrequenztechnik, Technische Universität Darmstadt, 64283 Darmstadt, Germany
[2] Merck KGaA, Liquid Crystal Division, Darmstadt, Germany

*Abstract* — **This paper introduces an alternative low-cost planar integrated, tunable Liquid Crystal phase shifter device for microwave applications, using the dielectric anisotropy of a nematic liquid crystal in conjunction with the inverted-microstrip technology and a DC control voltage. With a standard nematic liquid crystal a differential phase shift of 53° was achieved at 18 GHz for a physical line length of 49 mm, indicating a figure-of-merit of up to 12°/dB with a control voltage of only 40 V and a very low power consumption of 0.1 mW. On this basis, the phase shifter performance can considerably be improved by miniaturizing the device and by optimizing liquid crystals in the microwave region, which will be carried out soon.**

## I. Introduction

Tunable microwave components such as phase shifters are needed as key components in phased-array antennas for automotive radar sensors and future generations of mobile communication systems. In recent years strong research interests have been focussed on passive tunable microwave components based on nonlinear dielectric materials, mainly ferro- or paraelectric materials, as promising alternatives to active semiconductor devices [1]. Planar devices integrated on tunable dielectrics combine the key benefits of small size, light weight, low cost, low power consumption and continuous electronical tuning.

Another promising option for nonlinear dielectrics are anisotropic nematic Liquid Crystals (LC) that are well known from optical Liquid Crystal Displays (LCD) [2]. Based upon the Fréedericksz-effect, the relative dielectric constant of a nematic liquid crystal can be changed by orienting the director of LC molecules relative to the excited RF field polarization with an electro-static or magneto-static field. Up to now, only few approaches have been made to make direct use of a microwave dielectric anisotropy for phase shifting purpose [3], [4], [5], [6]. However, the proposed devices do not fit significant demands such as low control voltages or power, small size and low cost. Moreover, no information about the device insertion losses is given in these publications. In this article, an integrated, broadband microwave phase shifter device is presented and fully characterized, that is of planar nature, and thus strongly relates to low-cost optical LC displays.

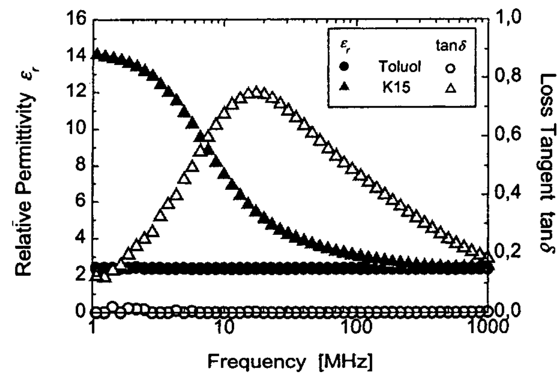


Fig. 1. Measured mean values of relative permittivity $\varepsilon_r$ and dielectric loss tangent $\tan\delta$ of nematic liquid crystal K15 and Toluol as a function of frequency at 25°C.

## II. Preliminary Studies On Nematic Liquid Crystals

A prototype nematic LC structure of high dielectric anisotropy is given by K15 (5CB) of Merck. At 1 MHz and 25°C a dielectric anisotropy of $\Delta\varepsilon_r = 13$ and a maximum relative permittivity of $\varepsilon_{r,\parallel} = 20$ was measured with a capacitive capillary cell. The nematic phase, i.e. the temperature range, where an anisotropy appears effectively, was measured to reach from 15°C to 35°C. Hence, K15 is an ideal candidate for a first demonstration of a microwave anisotropy at room temperature. To assure a well directed design of a microwave dielectric phase shifter, a precise knowledge of the liquid crystal dielectric properties is inevitable, regarding impedance matching and an estimation of the overall device performance. Therefore, and because of the rareness of available data, broadband dielectric measurements of LCs were carried out from 1 MHz to 1 GHz with a HP 4191 A LCR impedance analyzer using a parallel-plate capacitor technique. Fig. 1 shows the measurement results for the



0-7803-7239-5/02/$10.00 © 2002 IEEE

mean values of the relative permittivity and the dielectric loss tangent of LC K15 without any external LC orientation at a temperature of 25°C. In addition, the non-polar liquid Toluol was measured as a reference to verify the high measurement accuracy. For LC K15 a dominant relaxation absorption band is observed in the lower MHz region due to a molecular rotation around the short molecule axis, as typical for nematic LCs. Therefore, nematic liquid crystals are less qualified for MHz frequencies, but applications at X- or Ku-band frequencies or even in the millimeterwave region should be very encouraging. The relative permittivity strongly reduces with increasing frequency to a nearly constant value of $\varepsilon_r = 2.53$ at 1 GHz. Since no further significant relaxation phenomena are presumed up to the millimeterwave region, it seems to be reasonable to use this permittivity value as a design parameter for the microwave phase shifter device.

## III. Inverted-Microstrip Phase Shifter

The concept of the planar integrated inverted-microstrip transmission line [7] fits the goal of forming a low cost liquid crystal microwave phase shifter very well. It offers the benefit of very low requirements of LC, where the microwave signal is dominantly guided in the LC dielectric to make best use of its anisotropy.

### A. Phase Shifter Design

A cross-section of the inverted-microstrip phase shifter is illustrated in Fig. 2. The upper microstrip-line and the ground plane consist of 18 μm gold-plated copper metallizations, being supported by commercial low permittivity composite ceramic substrates TMM3 ($\varepsilon_r = 3.27$) of Rogers Corp. Both substrates are seperated from each other by a teflon seal, forming a fixed volume for the LC to be filled in. Thin polyimide films of approximately 300 nm thickness are spin coated on both substrate surfaces. A very fine, one-dimensional microstructure is rubbed into the polyimide in order to obtain a planar alignment of the LC-molecules parallel to the surfaces, i.e. perpendicular to the microstrip field. In this default device state a relative LC permittivity of $\varepsilon_{r,\perp}$ is effective. If an electrical tuning voltage is applied between the stripline and the ground metallization, the directors of the nematic LC molecules are forced to orient parallel to the polarization of the microwave field. This results in a higher value of permittivity due to an increased effective dipole moment. For sufficiently high voltages the polarization of the LC molecules saturates and a maximum relative permittivity $\varepsilon_{r,\parallel}$ is observed. This continuous, voltage-controlled tuning of the relative permittivity with a maximum dielectric anisotropy of $\Delta\varepsilon_r = \varepsilon_{r,\parallel} - \varepsilon_{r,\perp}$ can be used directly for phase shifting purpose at microwave frequencies. The maximum differential phase shift of a dielectric LC phase shifter can be written as

$$\Delta\Phi = \frac{2\pi f}{c_0} L \left(\sqrt{\varepsilon_{r,eff,\parallel}} - \sqrt{\varepsilon_{r,eff,\perp}}\right) = \frac{2\pi f}{c_0} L \, \Delta n_{eff} \quad , \quad (1)$$

where $\Delta n_{eff}$ is the effective anisotropy of the refraction index, $f$ is the frequency of operation, $L$ is the physical length of the phase shifter, and $c_0$ is the speed of light.

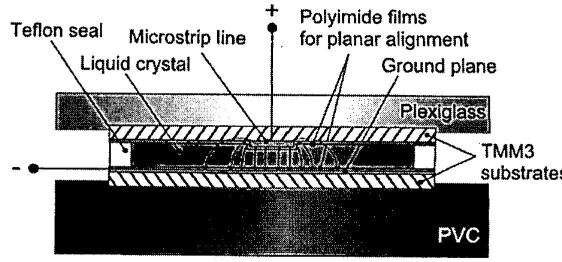


Fig. 2. Concept of an inverted-microstrip phase shifter using a nematic LC as tunable dielectric material. The LC molecules are pre-aligned by micro-structured polyimide films and can be oriented by a DC voltage parallel to the polarization of the microwave field.

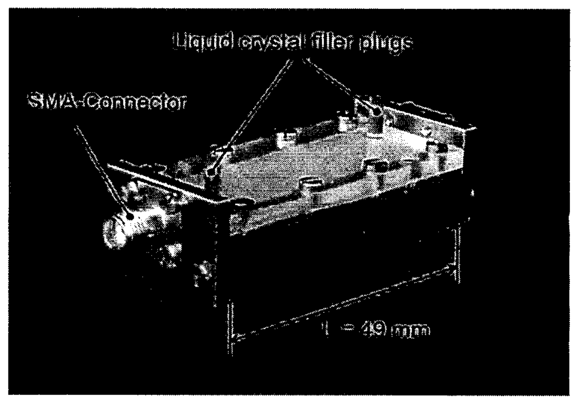


Fig. 3. Photograph of the fully packaged liquid-crystal phase shifter device with coaxial SMA connectors and filler plugs.

The microstrip-line geometry is designed to match a line impedance of 50 Ω using a quasi-static model for microstrip lines in a multilayer dielectric environment based on variational methods [8]. Assuming a LC permittivity of 2.5 and a fixed teflon seal height of 230 μm a microstrip line width of 600 μm is chosen. The physical line length of the LC filled microstrip line section amounts to 49 mm. Common SMA connectors are used in order to connect the inverted-microstrip phase shifter to a coaxial measurement system. The SMA connectors are provided with soldered strips of thin gold foil that are clamped in between the microstrip line and the teflon seal. The liquid crystal is filled in one of the two filler plugs using capillary attraction, as can be seen from Fig. 3.

*B. Results And Discussion*

The scattering parameters of the completely packaged phase shifter device filled with LC K15 were measured with an HP 8510 B network analyzer from 100 MHz up to 18 GHz. Fig. 4 shows results for the magnitudes of the scattering parameters for a control voltage of 0 V and 40 V, respectively. The input match and insertion loss at 50 Ω are strongly affected by the coaxial-microstrip transition. However, a return loss $|S_{11}|$ lower than −10 dB is achieved over the whole frequency band up to 18 GHz. Return and insertion loss will be significantly improved, if the inverted-microstrip phase shifter is embedded in a microstrip only circuit environment. The additional insertion loss due to the liquid crystal was extracted using a reference measurement with Teflon dielectric and amounts to 1 to 2 dB at 10 GHz, depending on the applied control voltage. This corresponds to loss tangent values between 0.02 and 0.03 for LC K15.

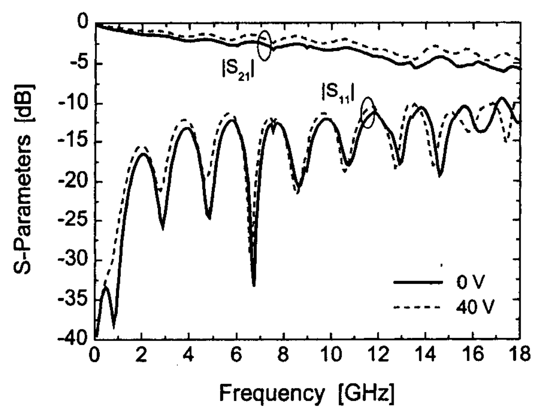


Fig. 4. Measured scattering parameters of the phase shifter device vs. frequency for 0 V and 40 V control voltage.

The differential phase shift is plotted vs. the applied control voltage in Fig. 5 for 10 and 18 GHz. Above a certain threshold voltage of approximately 5 V, the Fréedericksz transition [2], a nearly abrupt increase of phase shift is observed that is limited by saturation of polarization. For voltages above 40 V there is no significant increase of the differential phase shift, anymore. This low voltage operation is accompanied by a very low power consumption of only 0.1 mW at a maximum control voltage of 40 V. Only a very small hysteresis was observed for the measured differential phase shift as a function of increasing or decreasing control voltage.

The effective anisotropy in terms of $\Delta n_{eff}$ extracted from the measured differential phase shift according to eq. (1) is between 0.045 and 0.05 in the frequency range between 10 and 18 GHz, but it is well below its observed optical anisotropy.

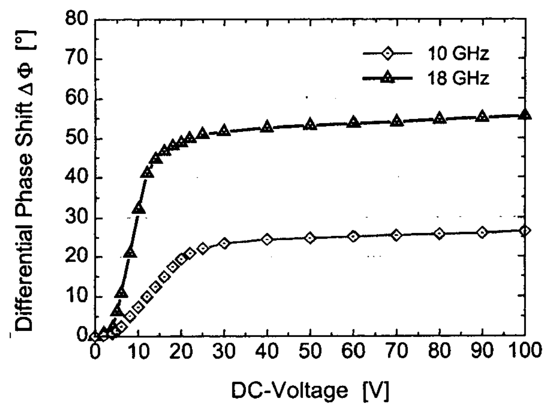


Fig. 5. Differential phase shift as a function of applied DC voltage at 10 GHz and 18 GHz, respectively. The physical LC-phase shifter line length is 49 mm.

The switching time between the two extreme LC orientational states is typically about 20 ms for a switched-on control voltage parallel to the microwave field. It depends on the rotational viscosity of the LC and can be accelarated by the applied control voltage and by reducing the gap between microstrip line and ground plane [2]. The re-orientation time back to the initial state of LC alignment, without any present electrical field, is considerably higher, since it is determined by elastic properties and viscosity of the LC, and the cell gap, only. In order to accelerate the re-orientation, our current design activities deal with a miniaturization of the microstrip line geometry and modifications on the ground plane, so that a second external electrical field for orientation can be applied perpendicular to the present one.

The decisive quantity for a microwave phase shifter is the quotient of differential phase shift and insertion loss, here denoted as Figure-of-Merit:

$$\text{Figure-of-Merit} = \frac{\text{Differential Phase Shift}}{\text{Insertion Loss}} \quad [°/\text{dB}]. \quad (2)$$

The measured Figure-of-Merit as a function of frequency is presented in Fig. 6 on the basis of the insertion loss at 0 V and 40 V, respectively. The ripple of the measured insertion loss has been smoothed for a more convenient illustration. The Figure-of-Merit is nearly constant over X-band and Ku-band with values between 8 and 12°/dB, depending on the applied control voltage. These first results for a standard nematic LC are quite comparable to the reported performance of ferroelectric phase shifters and thus very encouraging. Therefore, our current investigations are already focussed on a well directed synthesis of LC structures optimized for microwave frequencies or liquid artificial dielectrics as proposed by [3], that should lead to clearly higher values of anisotropy, i.e. higher differential phase shifts.

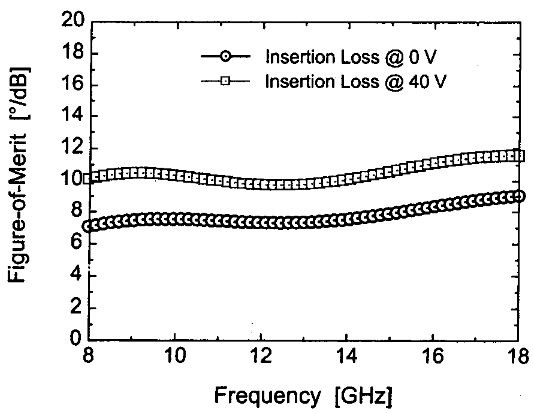


Fig. 6. Phase shifter Figure-of-Merit as a function of frequency, covering X-band and Ku-band. The two plotted curves are related to the insertion loss at 0 V and 40 V, respectively.

## IV. Conclusion

A tunable dielectric phase shifter device has been introduced for X-band and Ku-band frequencies making use of the dielectric anisotropy of a prototype nematic liquid crystal. The inverted-microstrip technology in connection with a very low amount of liquid crystal results in significant benefits as small size, light weight, low cost, low voltage (40 V), and low power (0.1 mW) operation. With a demonstrating device of 49 mm line length a differential phase shift of 53° was achieved at 18 GHz with a maximum figure-of-merit of 12°/dB. The differential phase shift can be distinctly improved by applying liquid crystals with optimized microwave anisotropy. Anisotropy values of $\Delta n > 0.2$ are already reported in the microwave region [4] and should result in figure-of-merit values greater than 50°/dB. Thus, the reported liquid crystal inverted-microstrip phase shifter device is a very promising candidate for a low-cost passive phase shifter for microwave or even millimeterwave applications.

## Acknowledgement

The first author is grateful to Dipl.-Ing. D. Ganzke at Institute of Physical Chemistry, Technische Universität Darmstadt for helpful discussions.

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