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Novel Hybrid Electric/Magnetic Bias Concept for Tunable Liquid Crystal Based Filter

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ABSTRACT This paper presents a novel hybrid bias concept for liquid crystal (LC) filter by using simultaneously electric and magnetic bias fields. It enables continuous tuning with a simplified electrode design, decreased number of electrodes and reduced bias voltage. Furthermore, the tuning efficiency is increased, since the homogeneous bias fields enable a full exploitation of the LC's anisotropy. To demonstrate this concept, a novel reconfigurable gap waveguide two-pole bandpass filter with tunable center frequency and coupling elements is designed at 30 GHz. Liquid crystal technology is applied as tunable material, whereby tunability of the center frequency and coupling elements is obtained by controlling the LC's effective permittivity. The presented filter's center frequency can be tuned from 28.88 GHz to 29.88 GHz with a maximum bias voltage of 100 V, with a return loss of 20 dB and low insertion loss of only 1.65 to 1.95 dB.

INDEX TERMS K-band, liquid crystals, microwave filter, millimeter wave communication, tunable circuits and devices.

I. INTRODUCTION

Future wireless communication systems must satisfy the increasing demand for higher data rates, while the frequency spectrum is limited. Therefore, the millimeter wave (mmW) regime gains more and more interest, due to the larger available bandwidths. Furthermore, reconfigurable RF front-ends are required to enable a highly efficient usage of the spectrum and for bandless systems such as cognitive radio or software defined radio. For these front-ends, reconfigurable filters are key components. To obtain tunability, different technologies can be applied as e.g., microelectromechanical systems (MEMS) [1], semiconductors [2], barium strontium titanate (BST) [3] and liquid crystals (LC) [4]. In this paper, LC is utilized as tunable material, since it enables continuous tunability with low power consumption and has moderate dielectric losses in the mmW regime [5]. Moreover, it has no mechanical moving parts, which can cause wear-out failures. In a previous work [6], a bandwidth and center frequency reconfigurable LC filter has been reported in waveguide technology. However, the integration of the electrodes into the waveguide is very challenging and, furthermore, deformation of the metal, fabrication flaws and imperfect assembly lead to degraded RF performance. Another drawback is the high bias voltage of ±250 V. Therefore, a novel hybrid bias concept for tunable LC filter is investigated in this paper. By simultaneously applied magnetic and electric bias fields, the LC's effective permittivity can be controlled with a reduced number of electrodes, lower bias voltage and higher tuning efficiency. Furthermore, a groove gap waveguide (GGW) technology is chosen for to implement the LC filter instead of a rectangular waveguide as in [6], since it offers the unique advantage of DC-decoupled metal line sections at the top and bottom according to Fig. 1(a), while maintaining similar low insertion losses than rectangular waveguides [7]. DC decoupling is achieved by the small gap between the bed of nails structure at the bottom and the top metal plate, in which no propagation is possible, due to an electromagnetic stopband. This simplifies the electrode system in particular with the hybrid bias concept,

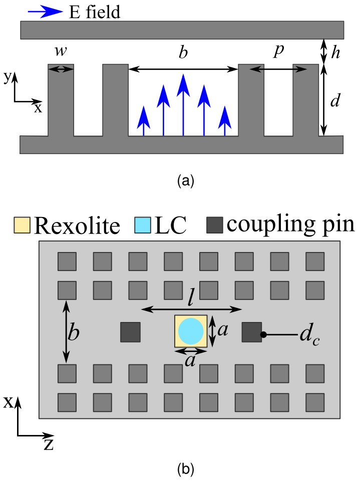


FIGURE 1. (a) Cross-section of the designed groove gap waveguide with two pin rows on each side. (b) Top view of a tunable LC groove gap waveguide resonator, which has two pins (dark gray) as coupling elements.

and hence, the assembly of the filter significantly compared to the one in [6], since the bed of nails structure at the bottom is used at the same time as ground plane for the bias voltages to tune the resonators. This GGW technology has been already used and proven for fixed high-Q filters [8] and tunable LC phase shifters [9], but not yet for tunable filters.

II. RECONFIGURABLE GAP WAVEGUIDE LC FILTER

A. LC TECHNOLOGY

In this work, LC is used in its nematic phase, which is between the isotropic liquid state and the solid crystalline state, depending on the temperature for thermotropic LCs. As the name indicates, it has simultaneously properties of liquids and crystals. While remaining in an orientational order, it can flow like a liquid. Furthermore, calamitic LC with rod-like shaped molecules are used in this work. Since its relative permittivity is different for its long and short axis with $\varepsilon_{r,\parallel}$ and $\varepsilon_{r,\perp}$, respectively, its anisotropy is defined by $\Delta\varepsilon = \varepsilon_{r,\parallel} - \varepsilon_{r,\perp}$. Therefore, depending on the LC molecules' orientation to the applied electrical RF field, the effective permittivity and, furthermore, its loss tangent changes. Due to the LC's polarizability, the orientation of the molecules can be controlled by external electrical and magnetic bias fields, which are generating electric and magnetic dipole moments, respectively. By applying an external bias field, the energy in the LC volume is increased. To obtain a state of equilibrium inside the LC cavity, the molecules align themselves parallel to the bias field lines. Hence, by controlling the LC molecules' orientation with respect to the RF-field polarization, the effective permittivity is controlled. A detailed overview of LC technology is given in [5], [8]. The applied GT7-29001 mixture from Merck KGaA is specifically synthesized for microwave applications. It has the following electrical properties at 19 GHz [9]: $\varepsilon_{\perp,r} = 2.46$, $\varepsilon_{\parallel,r} = 3.53$, $\tan\delta_{\perp} = 1.16 \cdot 10^{-2}$ and $\tan\delta_{\parallel} = 0.64 \cdot 10^{-2}$.

B. GROOVE GAP WAVEGUIDE

The GGW [10] consists of two parallel metal plates, being DC decoupled. The top plate is smooth, whereas the bottom plate is patterned with a bed of nails consisting of rectangular bars, which acts as a metamaterial surface, as shown in Fig. 1(a). A stopband characteristic is obtained between the top plate, which can be seen as a perfect electrical conductor, and the bed of nails structure, which acts as an artificial perfect magnetic conductor, if the condition for the distance with $d < \lambda/4$ is fulfilled. The GGW is optimized for 30 GHz and has the following dimensions in mm: $b = 7.1$, $h = 2.6$, $d = 0.175$, $p = 3.8$ and $w = 1.4$. The dispersion diagram of the bed of nails unit cell is obtained by using the eigenmode solver of CST Studio Suite, where the results for the Brillouine zone are depicted in Fig. 2 for the first three modes. The stopband is ranging from 18 GHz to 48 GHz, which determines the operation range of the GGW. Furthermore, simulations were conducted to obtain the attenuation of the electrical field in dependency of the number of pin rows in x-direction. The electrical field is attenuated by 29.5 dB and 44.6 dB in x-direction for two and three rows, respectively.

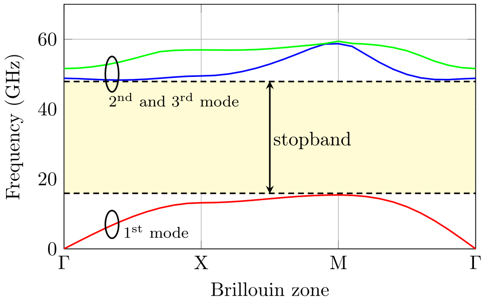


FIGURE 2. Simulated dispersion diagram for the bed of nails unit cell.

The top view of a tunable LC GGW resonator is presented in Fig. 1(b). It consists of two coupling pins and a quadratic LC-cavity in its center, which has the same height d as the GGW pins. Rexolite is chosen for the cavity, since its permittivity $\varepsilon_r = 2.53$ is similar to LC and it has a low loss tangent $\tan\delta = 0.66 \cdot 10^{-3}$. By varying the length l of the resonator and the size of the LC-cavity a, the resonance frequency is controlled. For larger LC cavities, the tuning range of the resonance frequency is increasing, but the quality factor is decreasing. To adjust the coupling, d_c is varied.

C. RECONFIGURABLE LC GGW FILTER

In this section, a center frequency tunable second order bandpass filter with adjustable coupling strengths is designed in GGW technology, which is operating at 30 GHz with an intermediate equal ripple bandwidth (BW) of 300 MHz and a return loss (RL) of 20 dB. Similar to our previous work [6], two main resonators (MR) and three coupling resonators (CR), which resonate at frequencies far below the passband, are used to design a reconfigurable filter. By inserting LC into the MR and CR and controlling the LCs' permittivity, the center frequency of each resonator can be tuned independently. The CR act as adjustable impedance inverters, which are used to adjust the coupling strengths [11].

The LC cavities are identical for all resonators, with $a = 2.6$ mm and $d_{LC} = 2.2$ mm, to enable a center frequency tuning of 3.4%. Therefore, bandwidth tuning is limited, however,

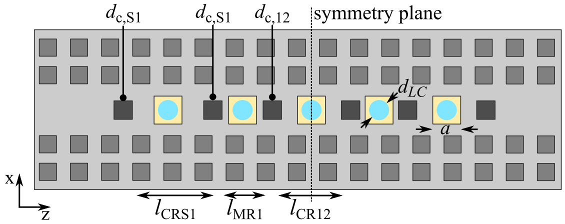
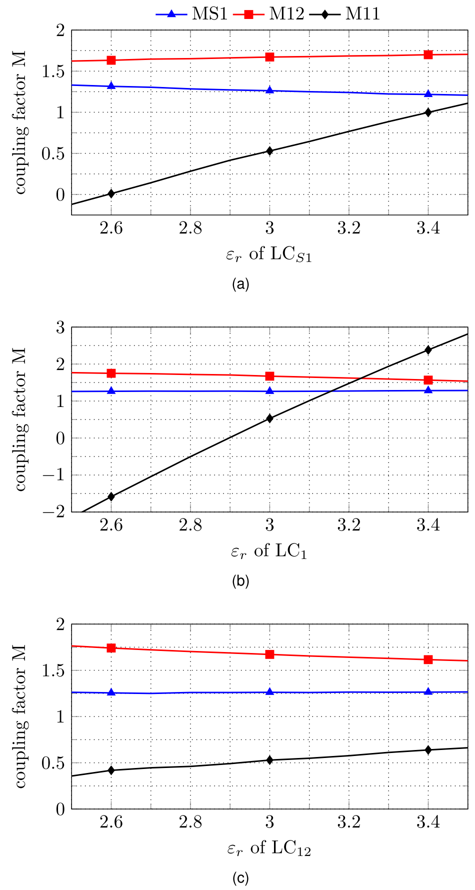


FIGURE 3. Top view of the reconfigurable filter model. Dimensions in mm: $l_{CRS1} = 9.7$, $l_{MR1} = 5$, $l_{CR12} = 9.7$, $d_{c,S1} = 0.87$, $d_{c,12} = 1.48$, $a = 2.6$, $d_{LC} = 2.2$.



(a)

(b)

(c)

FIGURE 4. Simulation results of the extracted coupling factors ($n = 2$, *BW* = 300 MHz, $f_0 = 30$ GHz, *RL* = 20 dB) when the relative permittivity of the corresponding resonator is changed. The relative permittivity of the other resonators remains at $\varepsilon_r = 3$ (a) first and last coupling resonators are changed (b) first and second main resonators are changed (c) inter-resonator coupling resonator is changed.

tuning of the center frequency with constant filter characteristic is possible. Hence, the resonators only differ in their length l and coupling pins height d_c. More information regarding the design process can be found in previous work [6].

The model of the resulting filter with its dimensions are given in Fig. 3, where the Rexolite cavities have the same height as the metal pins and their bottoms have a thickness of 100 μm.

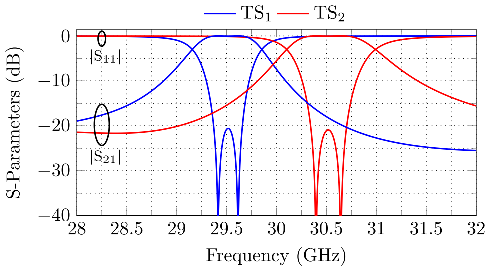


FIGURE 5. Simulated lossless tuning states (TS) at lowest and highest center frequency, respectively.

In Fig. 4, a coupling factor analysis is performed to investigate the influence of the resonators on the filter performance. The LC in all resonators is set to $\varepsilon_r = 3$, while the permittivity of the corresponding resonators is swept from $\varepsilon_{min} = 2.5$ to $\varepsilon_{max} = 3.5$. Fig. 4(a) shows the effect of the coupling resonator on the coupling factor entries M_{S1}, M_{12} and M_{11}. An influence on all three entries can be seen. As depicted in Fig. 4(a), the permittivity change of the main resonator's LC has only a small influence on the coupling between the resonators and none on the input coupling. In contrast, Fig. 4(c), a significant effect can be seen on the coupling between the resonators. Therefore, the resonators can be tuned to provide the required coupling and self-resonance for constant return loss over a wide tuning range.

CST Microwave Studio has been used for simulations, two simulated tuning states (TS) for lowest and highest center frequency, respectively, are shown in Fig. 5.

D. HYBRID LC BIASING CONCEPT

For reconfiguration of the filter, each MR and CR must be individually and independently tunable. By applying LC into the resonators and controlling its molecules' orientation, the resonance frequency can be tuned, since a change of the permittivity leads to a change of the resonator's electrical length. In Fig. 6(a) an electrode arrangement for fully electrical LC biasing is presented. It shows the bias fields for orthogonal biasing, with $U_{b2} = 0\,\text{V}$, $U_{b1} = U_{b4} = +V$ and $U_{b3} = U_{b5} = -V$. It can be seen, that the bias fields are bent, hence, the LC orientation is not uniform. Therefore, the LC's anisotropy can not be completely exploited, since the molecules are not aligned fully orthogonal to the RF-field. In the design process, the electrodes' spacing and size have to be optimized such, that the bias field is as uniform as possible. However, the simulation time and effort is high, due to the comparatively small dimensions of the electrode structures.

In this paper, for the first time, an LC filter is biased by using the superposition of simultaneous electric and magnetic bias fields. The main advantage is that in contrast to electrodes, magnets can be placed outside the resonator. Hence, they do not have an impact on the RF-performance and can provide a uniform bias field inside the LC cavity, and hence, the LC's anisotropy can be fully exploited. This enables a simplification of the electrode design, since no perpendicular electrical field is necessary. As shown in Fig. 6(a) and [6], at least five electrodes are necessary for each resonator for fully electrical bias, whereas for the proposed bias concept, only one electrode is needed. Additionally, the maximum bias voltage is reduced, since in contrast to the perpendicular orientation, the parallel orientation requires lower bias voltages.

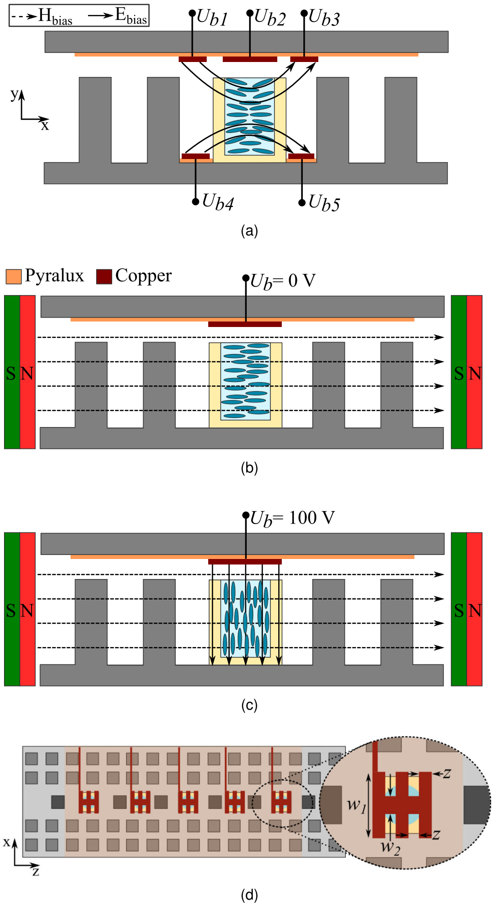


FIGURE 6. (a) Typical electrode arrangement for fully electrical biasing. (b), (c) Hybrid bias concept, using magnetic and electric fields for LC orientation. (d) Electrode design including the unwanted mode suppressing structure with following dimensions in mm: $w_1 = 2.80$, $w_2 = 0.40$ and $z = 0.56$.

The hybrid bias concept is depicted in Fig. 6(b) and 6(c). To align the LC molecules orthogonal to the applied RF field, two permanent rare earth magnets are placed next to the filter, providing a magnetic flux density of $B = 146\,\mathrm{mT}$, as shown in Fig. 6(b). By applying a rectangular 1 kHz bias voltage U_b to the copper electrode, an electric bias field is generated. If the bias voltages exceed a certain threshold voltage, the molecules will start to orient themselves parallel to the RF-field. By increasing the bias voltage, the LC molecules can be rotated from orthogonal to parallel orientation and vice versa. Hence, the effective permittivity is controlled by varying the amplitude. For a bias voltage of $U_b = 100\,\mathrm{V}$, the molecules are fully orientated parallel to the RF field, as shown in Fig. 6(c). By using an individual bias voltage for each resonator, as depicted in Fig 6(d), the resonators can be tuned independently.

For isolation of the top metal plate and the electrodes, a thin Pyralux substrate is used. To prevent parasitic mode excitation in this substrate, which degrades the RF performance as shown in previous work [12], the electrodes have a stepped-impedance structure [6]. By using full-waves simulations, the electrode structure has been optimized to minimize the impact on the RF-performance for the whole tuning range.

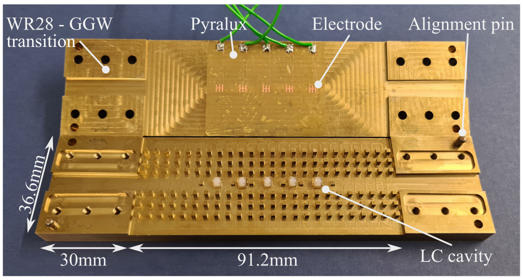


FIGURE 7. Photograph of the fabricated filter with WR28 to GGW transitions. The used magnets have a length of 100 mm and width of 35 mm.

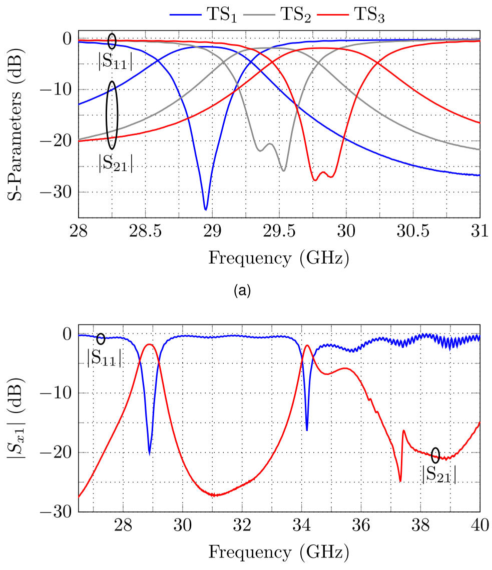
III. MEASUREMENT RESULTS

The filter including WR28 waveguide to GGW transitions is made of brass, using a high-precision CNC milling machine. It is displayed in Fig. 7. The Rexolite cavities are placed in the waveguide section using small alignment slots and are glued with UV adhesive. The electrodes are fabricated on a 12 μm thin DuPont Pyralux AP laminate with 9 μm thin copper clad by photolithography. Afterwards, they are placed on the top metal plate using wafer mounting wax. For LC filling, a syringe is used. After the filter is assembled, it is characterized by using a Keysight PNA-X N5247 A. In Fig. 8(a) different tuning states are shown, revealing an insertion loss (IL) between 1.65 dB and 1.95 dB, depending on the center frequency. For parallel orientation at high bias voltage, $\tan\delta$ of LC is lowest, hence, insertion loss for the lower center frequency is lowest, i.e., insertion loss is increasing with center frequency (lowering voltage). The measured insertion loss shows very good agreement with simulation, with a deviation of maximum 0.3 dB. In contrast to [6], the low deviation is a result of the novel bias concept and the lack of sidewalls of the GGW. Varying the 1 kHz rectangular bias voltages at the electrode allow a continuous change of the center frequency between 28.88 GHz and 29.88 GHz, while maintaining a return loss above 20 dB. Due to fabrication tolerances, the frequency range is shifted down by around 600 MHz. However, the filter's center frequency tunability of 3.4% is the same for measurement and simulation, since the applied bias concept has, especially for orthogonal orientation, homogeneous bias fields.Hence, a tuning efficiency of nearly 100% is achieved with a maximum bias voltage of 100 V, whereas for fully electrical LC filters like in [6] only 80% of the simulated tunability is achieved with bias voltages of $U_b > \pm 200\,\mathrm{V}$.

In Table 1 a comparison of state-of-the-art LC bandpass filters in different technologies is given. The main advantage of the presented filter is the low insertion loss, while maintaining a center frequency tunability of 3.4%. In [14], [15] higher center frequency tunability is achieved, but they have larger fractional bandwidths (FBW). Furthermore, the 3 dB bandwidth has a tunability in the range of 5.0% to 6.8%, which is, however, low compared to [6]. The wideband response over the whole Ka-band is presented in Fig. 8(b). The spurious

TABLE 1. Summary of State-of-the-Art Liquid Crystal Bandpass Filters

Work	Technology	Tuning Mechanism	BW tuning	f(GHz)	FBW	τ_{f_c}	τ_{BW}	IL(dB)
[13]	Microstrip	Electric field	no	50	18 %	10.3 %	/	3.8
[14]	Microstrip	Surface anchoring & electric field	no	33	10 %	5.7 %	/	4.5
[15]	Microstrip	Electric field	no	40	19.8 %	3.9 %	/	3.9
[16]	SIW	Electric field	no	30	11.4 %	2.3 %	/	2 - 4
[17]	HMCSIW	Surface anchoring & electric field	no	16.5	3.9 %	3.8 %	/	3.4
[18]	NRD	Electric field	no	60	1 %	2.9 %	/	4.2 - 6.2
[19]	Waveguide	Magnetic field	no	20	1 %	2.3 %	/	5.0 - 7.0
[6]	Waveguide	Electric field	yes	30	1 %	3 %	24 %	3.5 - 4.2
This	GGW	Electric & magnetic field	yes	30	1 %	3.4 %	5 %	1.65 - 1.95



(a)

(b)

FIGURE 8. (a) Measured S-Parameters at different center frequencies. From TS$_1$ to TS$_3$, the bias of the main resonators is lowered from 100 V to 0 V. (b) Measured wideband response for TS$_1$ for the whole Ka-band. The resonances of the coupling resonators are below the Ka-band.

modes between 34 GHz to 36 GHz are the TE$_{102}$ modes of the CRs.

IV. CONCLUSION

In this paper, a groove gap waveguide is used to design a bandpass filter based on liquid crystal technology for the first time. A novel hybrid bias concept using the superposition of simultaneous magnetic and electric bias fields is presented, which enables high tuning efficiency at relatively low bias voltages of up to 100 V only. The groove gap waveguide filter, designed at 30 GHz, shows very good agreement with the simulation. The insertion losses at all tuning states are below 1.95 dB, resulting in an unloaded Q-factor of $Q_u \approx 300$. A center frequency tunability of 3.4% is obtained while maintaining a return loss of 20 dB.

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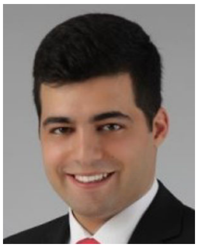

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