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MICROWAVE TUNABLE NOTCH FILTER BASED ON LIQUID CRYSTAL USING SPIRAL SPURLINE TECHNOLOGY

Javier Torrecilla,[1] E. Avila-Navarro,[2] Carlos Marcos,[1] Virginia Urruchi,[1] Jose M. Sanchez-Pena,[1] Julia Arias,[2] and Maria M. Sanchez-Lopez[3]

[1] Departamento de Tecnologia Electronica, Universidad Carlos III de Madrid, Leganes, Madrid 28911, Spain;
Corresponding author: jtorreci@ing.uc3m.es
[2] Departamento de Ciencia de Materiales, Optica y Tecnologia Electronica, Universidad Miguel Hernandez de Elche. Elche 03202, Spain.
[3] Instituto de Bioingenieria, Universidad Miguel Hernandez de Elche. Elche, 03202, Spain.

ABSTRACT: *In this article, the design, fabrication, and characteriza-tion of a tunable microwave notch filter based on liquid crystal (LC) using inverted-microstrip technology is presented. A spiral spurline structure is used because of its good performance as a single-resonator notch filter. Based on the LC dielectric anisotropy, a voltage-controlled rejection frequency of the filter is achieved, ranging from 3.40 to 3.75 GHz, which means that the tuning range relative to the central rejection frequency is about 10%. At the same time, this device exhibits negative group delay around the rejection frequency and the measured values throughout the tuning frequency range are presented.*

KEYWORDS: *LCs; notch filter; spiral spurline structure; tunable devices*

1. INTRODUCTION

The increasing interest in the development of tunable microwave devices has motivated the study of several approaches, such as the use of ferrite films [1], microelectromechanical systems [2] or varactor diodes [3].

Recently, the use of liquid crystals (LC) for the design of microwave tunable devices has become an interesting alternative due to benefits such as the possibility of small size, light weight, low cost, low-power consumption, and continuous electrically tuning. In particular, the dielectric permittivity value varies, upon application of an external electric field, between two extreme values, $\varepsilon_{r\perp}$ and $\varepsilon_{r\|}$, corresponding to two different orientations of the LC molecules. This fact allows LC to be used to design voltage-controlled tunable devices. Capacitors [4], phase shifters [5], antennas [6], and filters [7] are reported examples of LC tunable applications at microwave frequencies.

Conventional spurline structures are widely used as single-resonator notch filters in microstrip technology due to their good performance [8]. This kind of structure was used in a previous preliminary design of a LC-based tunable notch filter [9]. In this work, a variation of the conventional spurline structure, namely the spiral spurline structure, is considered instead as the spiral topology is expected to improve the filter selectivity and to reduce the device size [10]. A LC-based tunable notch filter of spiral spurline structure is therefore designed, fabricated, and characterized. The rejection frequency tuning is measured, as well as the negative group delay (NGD) variation, as a function of the applied external voltage.

2. DESIGN OF THE TUNABLE NOTCH FILTER

Spurline structures are microstrip single-resonator notch filters which offer a good band stop performance and easiness of manufacture.

These structures can be modeled by a parallel resistor-inductor-capacitor (RLC) circuit, where the inductance (L) and capacitance (C) values determine the filter rejection frequency and the resistance (R) models the filter losses [11]. Several kinds of spurline structures have been reported: conventional [8], meander [12], and spiral [10].

Figure 1(a) shows a conventional spurline notch filter structure which consists of a microstrip line separated into two coupled lines of a quarter wavelength at the central rejection

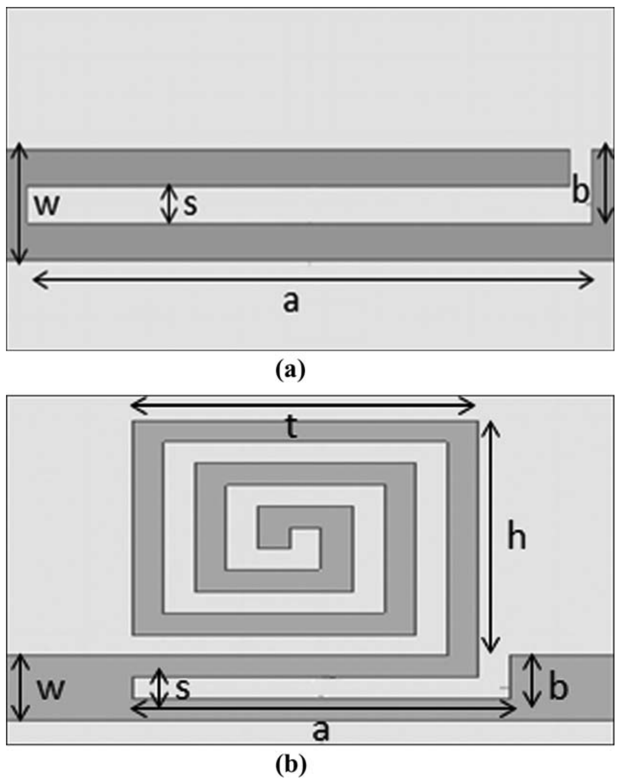


Figure 1 (a) Spurline structures considered. Conventional structure. (b) Spurline structures considered. Spiral structure

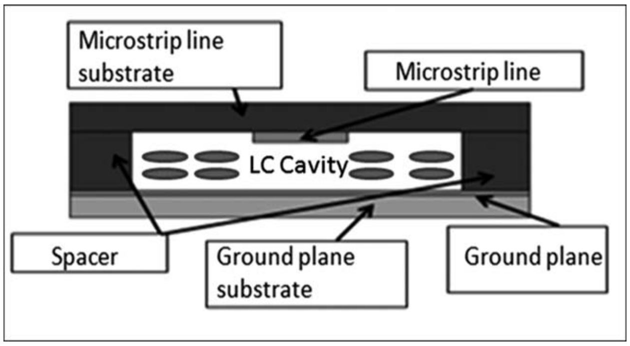


Figure 2 Notch filter based on LC. Detail of manufacture

frequency of the filter. Accordingly, the central rejection frequency, f_0, of a spurline notch filter can be calculated as a function of the coupled line length a as [8]:

$$f_0 = \frac{c}{4a\sqrt{\varepsilon_{\mathrm{eff}}}} \tag{1}$$

where c is the speed of light in vacuum and $\varepsilon_{\mathrm{eff}}$ is the microstrip line effective relative permittivity.

In the same way, if a spiral spurline structure, as the one shown in Figure 1(b), is used one can obtain f_0 using expression (1) by replacing a by the spiral equivalent length. Hence, for fixed dimensions of the spurline, the rejection frequency of the filter can be modified by changing the value of $\varepsilon_{\mathrm{eff}}$. This can be accomplished by using a LC-based substrate, where the relative dielectric constant can be tuned between two extreme values $\varepsilon_{r\perp}$ and $\varepsilon_{r|}$ by applying an external voltage.

In order to confine the LC inside the device, it is necessary to pour it into a cavity and then seal it. For this reason, the inverted-microstrip topology [13] shown in Figure 2 seems to be the most adequate to implement the filter.

Before filter manufacture, several simulations were run with the aim of setting the dimensions and comparing the spiral structure with the conventional spurline structure performance prior to the introduction of the LC. That is, the LC cavity was supposed to be empty (i.e., $\varepsilon_r = 1$) in these numerical calculations. Let us note that the dielectric permittivity of the LC to be used in our device is unknown at microwave frequencies, as it is recalled in Section 3. The electromagnetic analysis was done using the XFDTD$^{\mathrm{TM}}$ software, which is a commercial program by Remcom.

Taconic TLX-8, with dielectric constant $\varepsilon_r = 2.55$, is used for both a 0.8-mm thick substrate where the spurline is printed (labeled as "microstrip line substrate" in Fig. 2) and a 250-μm thick LC cavity spacer (labeled as "spacer" in Fig. 2). The dimensions of both the conventional and the spiral spurline structure were designed to obtain a rejection frequency near 5 GHz. The final dimensions of these structures are summarized in Table 1.

TABLE 1 Dimensions of a Conventional and a Spiral Spurline Structure both Designed for $f_0 = 5$ GHz

Dimension	Conventional (mm)	Spiral (mm)
a	11.2	2.4
b	0.4	0.4
s	0.2	0.2
w	0.6	0.6
t	–	2.2
h	–	2.2

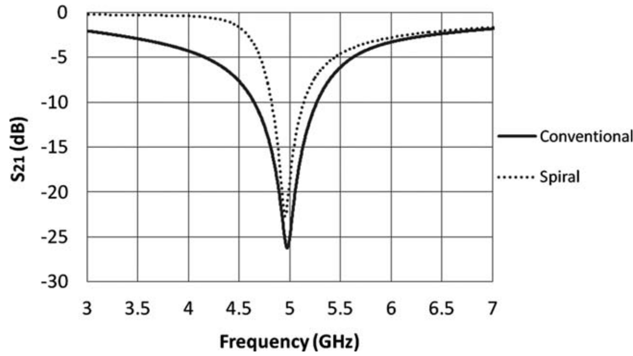


Figure 3 Simulation of the S_{21} parameter versus frequency for the conventional and spiral spurline structure. The LC cavity is considered empty

TABLE 2 Comparison of the Conventional and the Spiral Structure Simulated Performance

Structure	$Q = fo$/BW	Rejection (dB)	LC Cavity volume (mm^3)
Conventional	2.03	−26	26.4
Spiral	3.88	−22	11.22

The simulation results of the S_{21} parameter as a function of frequency for both structures are shown in Figure 3, and their performance is summarized in Table 2. Although the rejection at f_0 is better in the conventional structure, its spiral version presents a more selective response and a higher quality factor (Q). Moreover, the volume of the cavity is smaller, because of the smaller area in the spiral structure. This fact will involve an important cost reduction when dealing with LC-filled devices, as LC is a quite expensive material. This is the main reason for using the spiral topology in developing our tunable notch filter.

3. MANUFACTURE OF THE FILTER AND CHARACTERIZATION SET-UP

Once the spiral spurline notch filter (in its empty version) is successfully assessed by numerical simulations, it is fabricated with the dimensions indicated in Table 1 using Taconic TLX-8 as the supporting substrate for the microstrip line and spacer. The cavity is then filled with LC and sealed. The dielectric substrate attached below the ground plane is FR4 ($\varepsilon_r = 4.4$) with a thickness of 1.52 mm. This substrate is only used to provide support for the metallic plane, so it will not affect the filter behavior. The microstrip line width (w) is 0.6 mm in order to have an input impedance of about 50 Q.

The LC used to fill the 250-μm thick cavity is an experimental mixture of high birefringence. It is a nematic LC, 1631E, synthesized in Military University of Technology, whose behavior at microwave frequencies has not been previously studied,

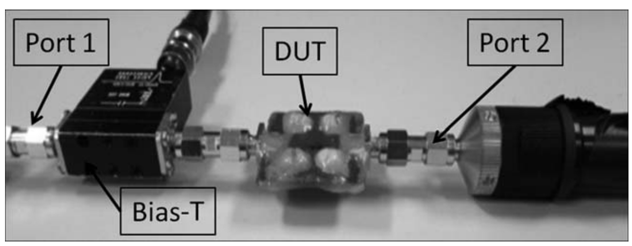
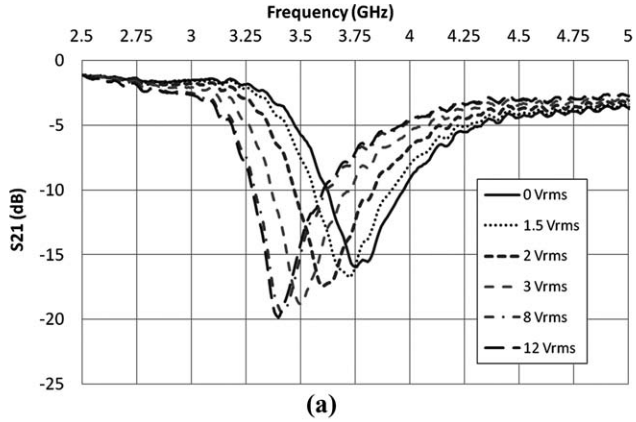


Figure 4 Detail of the setup for the frequency characterization of the notch filter



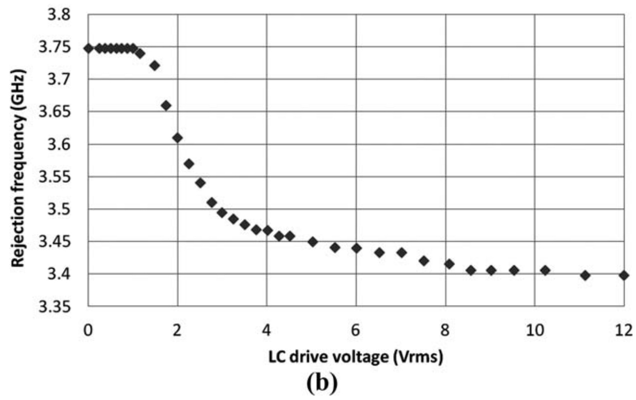


Figure 5 (a) Notch filter experimental results. S_{21} parameter of the notch filter as a function of frequency for several values of the LC drive voltage. (b) Notch filter experimental results. Rejection frequency as a function of the LC drive voltage

therefore, its loss tangent and dielectric permittivity extreme values are unknown at these frequencies.

In the manufacturing process, the LC molecules are aligned parallel to the microstrip line by using polyimide. Without voltage, the relative dielectric constant of the LC is $\varepsilon_{r\perp}$. As voltage is applied, the LC molecules rotate and the dielectric constant increases. At the saturation voltage value, the molecules lie perpendicular to the microstrip line and the relative dielectric constant is $\varepsilon_{r|}$. This fact allows the rejection frequency of the notch filter to be electrically controlled by applying an external voltage.

The frequency response of the filter was characterized by measuring the S-parameters with a two-port network analyzer Agilent 8703B. Port 1 of the analyzer was connected to the filter input through a bias-T to enable the overlay of the LC drive and the microwave signals. A sinusoidal alternate current signal of 1 kHz was used as LC drive voltage. Port 2 of the analyzer was connected directly to the filter output. The characterization setup is shown in Figure 4.

4. EXPERIMENTAL RESULTS

The magnitude of the S_{21} parameter of the notch filter was measured for LC drive voltage values ranging between 0 V_{rms} and 12 V_{rms}, as it is shown in Figure 5(a). Without external voltage, the LC dielectric permittivity is $\varepsilon_{r\perp}$ and $f_0 = 3.75$ GHz. A rejection frequency value below the one designed for the empty-cavity structure (5 GHz) was clearly expected because, although the LC relative permittivity was not known at this frequency, it is known to be greater than 1.

As the voltage increases, the LC dielectric permittivity also increases, while f_0 decreases. Upon applying 12 V_{rms}, the LC dielectric permittivity reaches its maximum value, $\varepsilon_{r\perp}$, and f_0 its minimum value, 3.40 GHz. This means a variation of the rejection frequency of 350 MHz across the tuning range, that is, a relative tuning range (with respect the central frequency) of 9.8% is obtained. In Figure 5(b), the evolution of the rejection frequency as a function of the applied LC drive voltage is shown.

An interesting aspect of notch filters is the existence of a NGD region at f_0. Therefore, as the rejection frequency is voltage controlled, NGD can also be frequency-shifted. Because of the increasing interest in microwave applications for NGD circuits [14,15], the group delay, τ_g, of the notch filter is also evaluated. It is calculated as the frequency derivative of the S_{21}-parameter phase, ϕ.

$$\tau_g = \frac{\partial \phi}{\partial \omega} \tag{2}$$

The frequency evolution of τ_g for several values of the LC drive voltage is shown in Figure 6. As f_0 is tuned from 3.40 to 3.75 GHz, the NGD region is accordingly shifted. This shift is accompanied by a variation of the group delay value at f_0, ranging from -1.6 ns at 3.40 GHz to -1.0 ns at 3.75 GHz. This is a consequence of the nonconstant rejection level at f_0 as the LC drive voltage is changed.

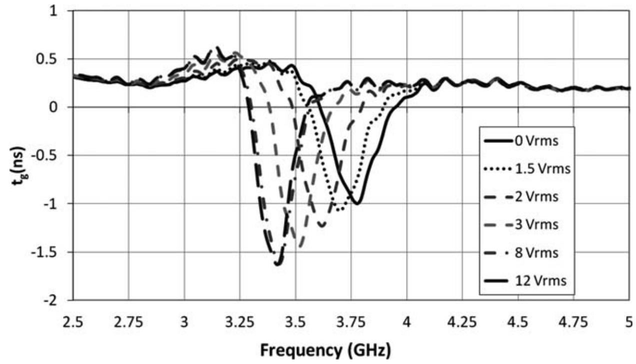


Figure 6 Evolution of the group delay with frequency for several values of the LC drive voltage

5. CONCLUSION

A LC-based tunable notch filter has been designed, fabricated, and measured. The device has been implemented in inverted-microstrip line technology using a spiral spurline structure as the notch filter. This structure provides an improvement of the filter performance and an important reduction of the device size with respect the conventional spurline topology. The key point is that the cavity volume is reduced by a factor of two and, consequently, the amount of the LC required is also reduced by this factor.

Because of the high dielectric anisotropy of the noncommercial LC used, a variation of the filter rejection frequency from 3.40 to 3.75 GHz upon applied voltage has been obtained, along with the corresponding frequency-shift of the NGD region. However, the experimental LC mixture used in this work was not tested for microwave frequencies, therefore its dielectric constant and losses are unknown. For estimating these values a method based on a combination of numerical simulations and measurements is currently being developed.

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