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Digitally Tunable Bandpass Filter for Cognitive Radio Applications

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***Abstract*—A lumped-element tunable pre-selection bandpass is presented that consists of three coupled resonators. The bandpass employs a digitally tunable capacitor (DTC) and allows for tuning of the centre frequency with a resolution of 5 bit. It covers the frequency range from 450 MHz to 940 MHz, including the DVB-T band, the TV white space (TVWS) band, and the LTE-800 frequency band. The insertion-loss variation amounts to 0.3 dB. The filter measures 20 mm by 20 mm, it can therefore be easily integrated into analog RF front-ends. The filter's application to cognitive-radio platforms is discussed.**

***Index Terms*—cognitive radio, digitally tunable capacitor (DTC), tunable bandpass filter**

I. Introduction

Cognitive radio (CR) is a new paradigm for wireless communication, where either the network or the wireless node itself changes certain transmission or reception parameters to efficiently execute its tasks [1]. To meet the resulting requirements the signal processing is moved as far as possible to the digital part. In many cases, software-defined radio (SDR) and CR systems merge with each other. The analog part, however, has to be tailored to the needs of a CR system as well, including the implementation of tunable pre-selection filters for CR or SDR operations.

In order to make an analog front-end more flexible, digitally tunable bandpass filter can be employed. Programmable filters have been known in audio and speech application for years [2]. High-quality tunable bandpass filters have already been used in CR systems [3]. However, these filters are often based on varactor diodes, requiring therefore a proper voltage control circuit. For example, a voltage-controlled MMIC bandpass filter is proposed in [5] that requires a tuning voltage of 0 V to 14 V for a tuning range from 1 GHz to 2 GHz. Among varactor diodes, RF MEMS components can be employed in tunable filters [4], but, on the one hand, RF MEMS suffer from a considerably shortened life cycle in contrast to components steered purely electronically, on the other hand, RF MEMS are still hardly available on the market. Depending on the technology, controlling an RF MEMS component may require an analog voltage and, therefore, a proper control circuit. Having the possibility to directly tune a filter using a digital control signal provided by a digital platform that exists in SDR systems anyway, requires little programming effort and no additional control modules.

In this paper, the design of a tunable bandpass filter (tBPF) programmable with a 3-wire bus system is proposed. The filter covers a wide tuning range from 470 MHz to 860 MHz, including the TV white space frequency band and LTE-800 frequency band. It can be employed in RF transmitter and receiver chains and provide low insertion loss variations.

By the means of simulation tools or dedicated filter implementation tools, filters based on lumped elements can be designed with little expenditure of time. Filter parameters such as center frequency, bandwidth, insertion loss, or stop-band rejection can be optimized. To reconfigure the filter characteristics, tunable elements are necessary that influence the filter parameters. The difficulty in the design of a tunable filter is to provide a wide-band matching and coupling, which usually consists of fixed elements. Thus, the optimum combination between tunable and fixed components have to be found to meet the requirements in terms of tuning range, bandwidth, and insertion loss.

The paper is organised as follows. Sec. II deals with the theory of the filter design, including the requirements and associated design challenges as well as with the discussion of simulation results. Sec. III discusses the implementation and measurement of a prototype filter. The integration into an RF transmitter front-end is additionally presented. A conclusion is given in Sec. IV.

II. Filter Design

The objectives pursued during the design of the bandpass stem from the requirements that were extracted from a publication of Ofcom on cognitive access on TV white spaces [6] as well as those being revealed in the European projects “SACRA” [7] and “QoSMOS” [3]. According to them, the frequency region to be covered ranges from 470 MHz to 862 MHz with a signal bandwidth of 40 MHz. The stop-band suppression was determined with respect to the transmit case, where, according to [6], a maximum transmit power of 20 dBm was presumed. Considering the maximum allowable power of out-of-band radiations of -44 dBm, a stop-band suppression of 64 dB is required at least. This suppression, though, concerns only emissions caused by higher-order harmonics of the RF transmit branch as well as the image frequency band. Out-of-band emissions near the RF signal cannot be suppressed by the tunable bandpass and are subject to the modulation scheme applied. Regarding the frequency response within the pass-band, two aspects are of interest:

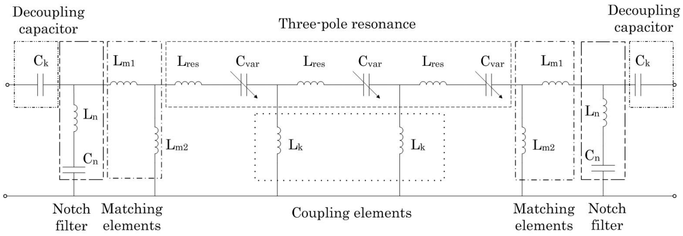

Fig. 1. Schematic of the tunable bandpass filter and labelling of its separate sections.

- Firstly, assuming a given state of the filter, the insertion loss within the pass-band itself is supposed to be as low as possible. This results in a higher efficiency that is particularly important for mobile devices.
- Secondly, concerning all possible states of the filter, the insertion loss is supposed to vary as little as possible with the tuning parameter(s). This simplifies the configuration of the front-end, as an equalization is no longer necessary.

A. Architecture

The filter architecture developed is portrayed in Fig. 1. As seen, the bandpass is based on three coupled resonators, each consisting of a variable capacitance C_{var} in series to an inductance L_{res}. The three resonators work at the same resonance frequency

$$f_{\text{res}} = \frac{1}{2\,\pi\,\sqrt{L_{\text{res}}\,C_{\text{var}}}}\,, \tag{1}$$

i.e., the centre frequency of the bandpass depends on a single tuning parameter only.

The number of resonators was determined considering the required stop-band suppression, the required signal bandwidth, and the tuning range of f_{res}. We therefore started to investigate an architecture using two coupled resonators. This architecture allows a wide tuning range in conjunction with a sufficient bandwidth, yet the required stop-band suppression cannot be achieved. Employing three resonators, however, revealed to be a proper trade-off: the stop-band suppression can be increased, while the tuning capability and the bandwidth is little affected.

Among the number of resonators, the bandwidth also depends on the kind and strength of coupling between them. As seen in Fig. 1, the coupling is done by shunt inductance L_{k}. Due to the inductive coupling, the quality factor and, therefore, the slew-rate are little influenced and both remain high [8].

The matching of the coupled resonators to the preceding and following sections is ensured by the inductances L_{m1} and L_{m2}. Before and after the matching section, respectively, a series resonator arranged as shunt circuit is located to ensure a wideband rejection up to 3.0 GHz. The resonator consists of capacitance C_{n} and inductance L_{n} and its resonance frequency follows from (1) with C_{var} substituted by C_{n} and L_{res} by L_{n}. C_{k} is a decoupling capacitance, which does not influence the RF signal.

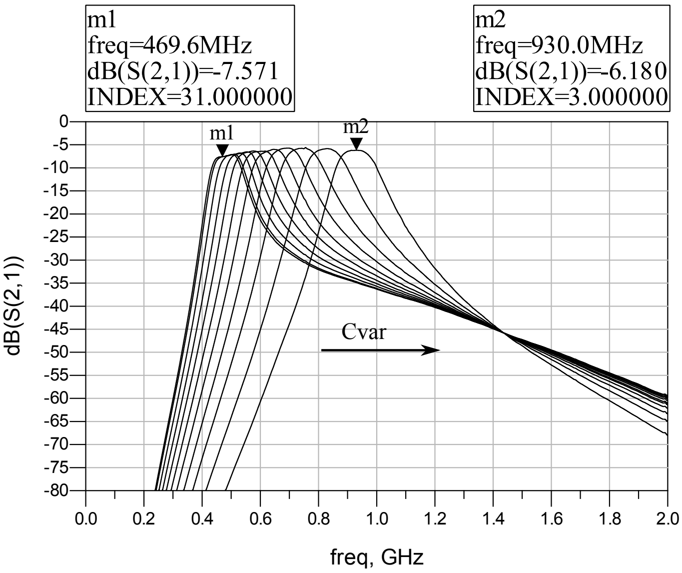

Fig. 2. Simulated amplitude response of the tuneable bandpass filter with C_{var} variable. The markers "m1" and "m2" point at the lower and upper frequency, respectively, according to the initial requirements.

B. Simulation

The frequency response of the filter was investigated by simulation [9]. As we aimed at a operating frequencies up to nearly 1.0 GHz and considering the tunability of the centre frequency, parasitic effects are expected to affect the filter characteristics. In the simulation model therefore the scattering parameters of the inductors chosen and the tuning element C_{var}were integrated.

Since the characteristic of C_{var} depends on its actual implementation, a proper component was identified at first. We decided to use a digitally tunable capacitor (DTC) [10] (PE64904 from Peregrine Seminconductor). The DTC possesses a 3-wire serial interface with which the effective capacitance can be selected. The capacitance can be varied from 0.6 pF to 4.6 pF with a resolution of 129 fF or 5 bit. In addition, the DTC also meets the linearity requirements necessary for the transmit case. Since the forward transmission depends on the quality factor of the resonator it influences the insertion loss in the passband of the most. In the simulation model, the scattering parameters over frequency measured and recorded for each individual state of the DTC were imported, allowing for an accurate prediction of the filter characteristics.

The filter amplitude response of the forward transmission coefficient s_{21} obtained from simulation is illustrated in Fig. 2 with C_{var} as parameter. The filter covers the tuning frequency range from 440.0 MHz to 940.0 MHz, while, according to (1), the lower C_{var} the higher f_{res}. The minimum 3 dB-bandwidth amounts to 40.0 MHz, as desired, which inherently increases with increasing resonance frequency. The simulation showed an insertion loss of 7.6 dB at 469.6 MHz and 6.2 dB at 930.0 MHz, respectively, with an acceptable variation of merely 1.4 dB. It revealed that about 2 dB to 3 dB of loss can be attributed to the DTC and the remaining amount to the

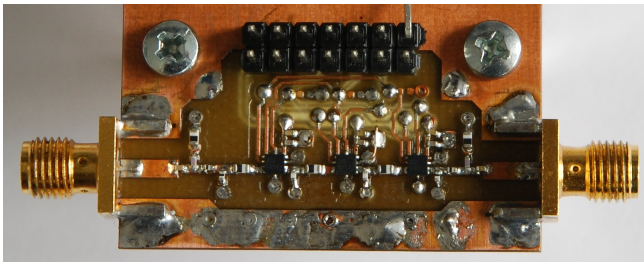

Fig. 3. Close-up of the prototype of the tuneable bandpass filter. The SMA jacks are to connect the RF source and load. The DTC is controlled by the connecting plug seen on the top.

imperfect inductors. Even though an out-of-band suppression of 64 dB cannot be achieved within the frequency range depicted, the filter suits the application needs in terms of tuning range, bandwidth, and insertion loss. Increasing the out-of-band suppression by adjusting the resonator coupling would lead to an reduced tuning range. To meet the requirements on the out-of-band suppression in the RF front-end chain, a tunable low-pass filter is going to be implemented, following the RF power amplifier. The low-pass is left out of dicussion here and may be subject of a further publication.

In Fig. 2, we notice that the amplitude flatness within the pass-band decreases with decreasing C_{var}. Yet by adjusting L_{m1} and L_{m2} appropriately, the ripple of the bandpass filter can be decreased. On the other hand, since an adaptation of particular reactances is expected during measurements, a further optimization of the simulation model was refrained.

III. Implementation and Measurement

A. Prototype

Before the bandpass was integrated into an RF front-end, a prototype version was implemented as depicted in Fig. 3. The board measures 42 mm × 25 mm in lateral dimensions and 1.06 mm in height. It consists of a signal layer and a ground layer and is based on an FR-4 substrate with a relative permittivity of 4.6. The supply voltage and the control signals are fed over an pin connector to all DTCs. As all resonsators are supposed to provide the same resonance frequency, the DTCs can be programmed at once, reducing the effort during circuit design. To control and program the prototype implementation, a programming adapter with USB interface was used in conjunction with the respective software, both provided by the manufacturer of the DTC [10].

B. Measurements

During measurements we figured out that the coupling inductance L_{k} has to be little adjusted. In the simulation model L_{k} was simulated with 4.7 nH, whereas the prototype value had to be changed to 2.7 nH. Furthermore the resonators inductance L_{res} had to be changed from 22 nH to 15 nH in order to achieve the required maximum f_c. The elements of the notch filter and the matching network of the tBPF manufactured could be adopted directly from simulations, i.e., $L_{\mathrm{n}} = 1.8$ nH, $C_{\mathrm{n}} = 1.8$ nH, $L_{\mathrm{m1}} = 4.7$ nH, $L_{\mathrm{m2}} = 10$ nH.

The measurement of the amplitude response of the forward transmission coefficient s_{21} with $C_{\mathrm{var}} = 4.18$ pF and $C_{\mathrm{var}} = 0.73$ pF, respectively, is illustrated in Fig. 4. The curves represent the cases with minimum and maximum centre frequency required, i.e., $f_{\mathrm{res}} = 470$ MHz and $f_{\mathrm{res}} = 860$ MHz, respectively. Compared with the simulation,

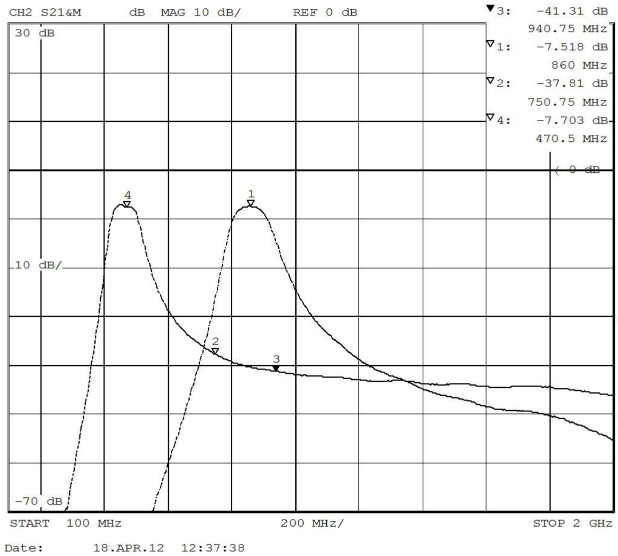

Fig. 4. Measured forward transmission amplitude over frequeny for the required minimum and maximum f_{res}, indicated by marker "4" and "1", respectively. Marker "2" and "3" show the stop-band transmission.

the insertion loss turned out to be higher as parasitic effects and additional ohmic losses are included in the measurements. At 470 MHz the insertion loss amounts to 7.7 dB, at 860 MHz to 7.5 dB, i.e., the insertion loss varies merely about 0.2 dB. For the pass-band around 470 MHz, the filter displays a 3-dB bandwidth of 40 MHz, which increases with increasing f_{res}. With $f_{\mathrm{res}} = 470$ MHz, the stop-band attentuation amounts to 37 dB at 750 MHz and to 41.3 dB at 940 MHz. In comparison with the simulated amplitude response, a difference can be observed, steming from the adjustment of L_{res} and L_{k}.

Figure 5 shows the input reflection coefficient s_{11} measured for $f_{\mathrm{res}} = 470$ MHz and $f_{\mathrm{res}} = 860$ MHz, respectively. A matching of 8 dB at least can be achieved within the tuning range required. To improve s_{11} (s_{22}) inductances L_{m1} and L_{m2} can be adjusted, but at the expense of the tuning range to be achieved.

The magnitude response $|s_{21}|$ of the tBPF with $C_{\mathrm{var}} = 4.6$ pF and $C_{\mathrm{var}} = 0.6$ pF, respectively, is shown in Fig. 6, illustrating the maximum tuning range that can be achieved by selecting the maximal and minimal DTC capacitance.

C. Integration

The tunable bandpass filter is implemented in an transmitter front-end and serves as image rejection filter. As seen in Fig. 7, it is located after up-conversion stage and before the signal is fed to the power amplifier (PA). The requirements in terms of power handling are therefore relaxed for the bandpass.

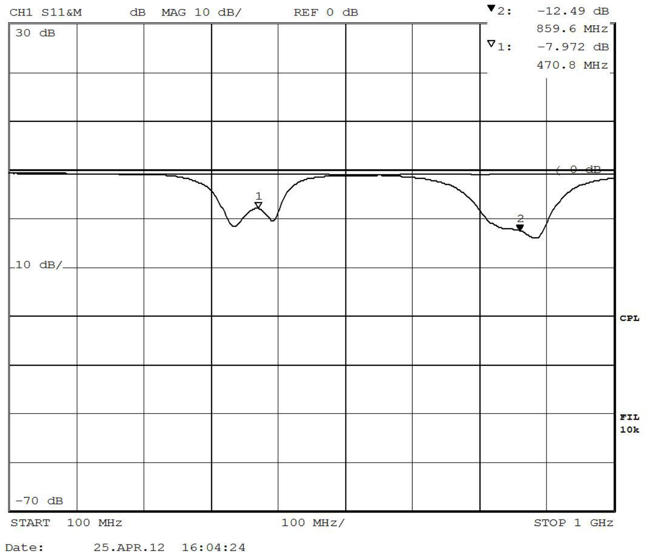

Fig. 5. Measured input reflection amplitude over frequency for the required minimum and maximum f_{res}. Marker “1” depicts the lower band, marker “2” the upper one.

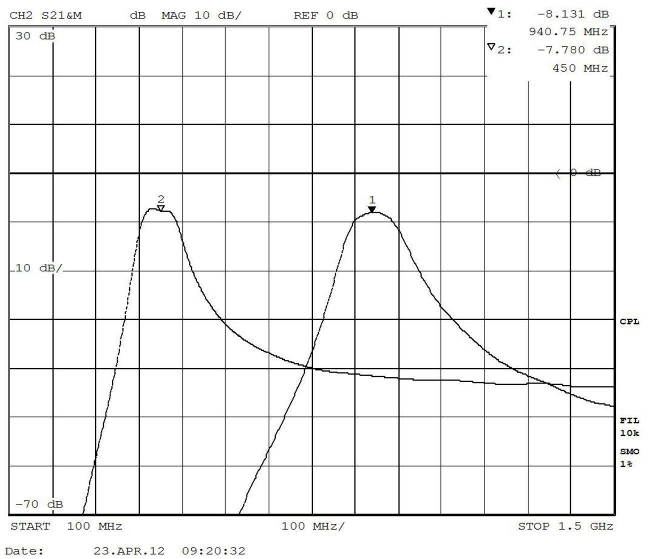

Fig. 6. Maximum measured tunability with marker ”1” at the highest and marker ”2” at the lowest f_c.

The integration of the tunable bandpass into an RF transmitter front-end is illustrated in Fig. 8, which shows the signal-layer layout of the transmitter front-end. In its integrated version, the filter occupies an area of approximately 40 mm^2. The control interface is provided by a proper connector (labelled “X202” in Fig. 8) that connects all analog and digital signals to a digital baseband board.

IV. Summary and Discussion

In this paper, a digitally tunable bandpass was presented. Starting with the requirements given for cognitive radio access within TV white spaces, we discussed the design and simulation of a filter architecture based on three coupled resonators. The resonance frequency of the resonators can be varied using a digitally tunable capacitance. Simulations displayed a tuning range from 370 MHz to 925 MHz.

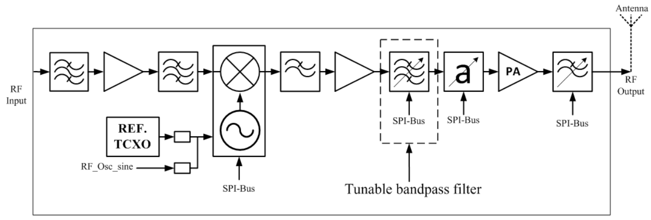

Fig. 7. Schematic view of the RF transmitter front-end [3] including the tunable bandpass filter

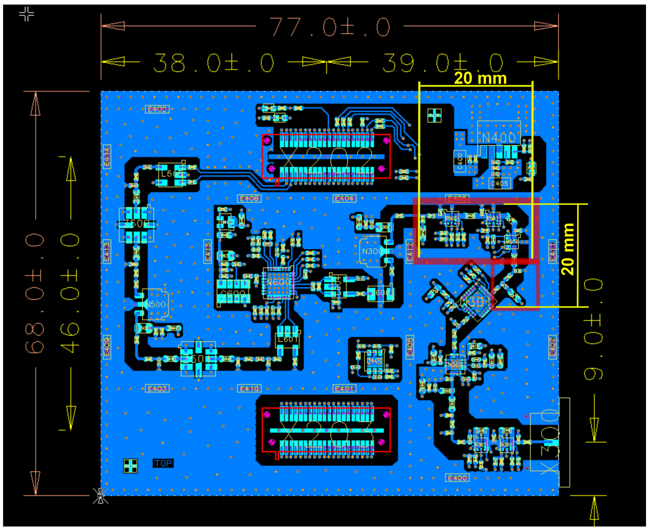

Fig. 8. Layout of the signal layer of the RF transmitter front-end. The area surrounded by red lines emphasise the integrated bandpass.

A prototype filter was implemented and characterized by measurements. According to the measurements, a tuning range from 450 MHz to 940 MHz was achieved with an insertion loss of 7.9 dB $\pm$ 0.15 dB. The insertion loss in the pass band can be further reduced by using special high-frequency inductors with less parasitic effects.

Considering the wide tuning range, the little insertion-loss variations, and the little dimensions, the bandpass represents a promising component to be applied to cognitive-radio systems. Here, the filter takes also advantage from the 3-wire programming interface that allows to control the centre frequency digitally, in line with the intentions of cognitive radio and software-defined radio. This digitally tunable bandpass filter can be employed in RF transceiver front-ends for cognitive-radio systems such as those designed in the projects SACRA [7] and QoSMOS [3].

The filter architecture proposed is basically independent of the frequency range to be addressed. By re-calculating the components appropriately, the filter can be adapted to be applicable within other frequency regions. For instance, another simulation model—left out of discussion here—have also been investigated that covers a frequency range from 1.8 to 2.8 GHz. In terms of the implementation, however, a proper technology have to be used. This holds for the tuning element as well as for the remaining reactive components. The DTC allows operation from 100 MHz to 3000 MHz, i.e., if higher frequency ranges want to be covered, another way of tuning have to be found such as varactor diodes, for instance. Regarding the reactive components, the implementation of lumped components becomes crucial with increasing frequency. For frequencies below 1 GHz, common surface-mount devices can be employed, for higher frequencies, however, parasitic effects increasingly affect the filter characteristic. I.e., either high-performance devices have to be used, coming along with higher costs, or an alternative implementation is required such as microstrip technology.

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