Ultra-compact MMIC active bandpass filter with wide tuning range

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A very wide tuning range CMOS MMIC bandpass filter is implemented using active coupled resonators and experimentally demonstrated. It can realise a 0.51 GHz frequency tuning range around 1.8 GHz using a single control voltage, with an ultra-compact size of 0.28 mm^2 and a very low DC power consumption of 41 mW.

Introduction: Coupled-resonator filters are an attractive solution for the realisation of fully monolithic active microwave bandpass filters because the filters can be devised to consist of only shunt LC resonators coupled by series capacitors. This approach requires only single-ended active inductors with one end grounded, which greatly reduces the size and power consumption of the inductors. Furthermore, coupled-resonator filters can eliminate impractically-different component values between shunt and series branches in Butterworth or Chebyshev filters and offer the most freedom in the selection of component values [1]. Previous researches [2–6] have validated this concept as a viable approach for tunable active filters using GaAs technologies.

In this Letter, we report a three-coupled-resonator CMOS MMIC active bandpass filter using three identical active inductors. This has two significant benefits: (i) any variations in the component values of the active inductors during fabrication will be consistent throughout the filter and can be more easily mitigated, and (ii) it makes the frequency tuning of the filter much more effortless because the resonant frequencies of all the resonators can be simultaneously varied using a single control voltage of the three identical active inductors. The fabricated bandpass filter is the smallest MMIC active filter of this type reported to date, five times smaller than the next smallest filter [6] (see Table 1). Note that the previous works used various III-V technologies while this work is the first in CMOS.

Table 1: Performance summary and comparison

Ref.	[2]	[3]	[4]	[5]	[6]	This work
Centre frequency (GHz)	1.8	2.27	2.0	4.7	2.32	1.82
Tuning range (GHz)	0.20	0.86	0	0	0.22	0.51
Size (mm^2)	2.4	4.96	5.5	–	1.44	0.28
DC power (mW)	704	300	–	150	25	41
Resonators	2	3	3	2	3	3
Technique	GaAs FET	GaAs FET	GaAs FET	GaAs FET	GaAs HBT	CMOS

Proposed MMIC bandpass filter: Fig. 1*a* illustrates the implemented bandpass filter using three active shunt resonators coupled by two coupling capacitors (C_C). Each of the three resonators consists of an inductor (L_{P1} or L_{P2}) and a shunt capacitor (C_{P1} or C_{P2}). The different shunt inductor values (L_{P1} and L_{P2}) are realised from the identical active inductors (AI) by connecting different series capacitors (C_{S1} and C_{S2}) of appropriate sizes to the active inductors, respectively, so that the reactance of each series capacitor subtracts a small amount from the reactance of each active inductor, which leads to an 'effective' shunt inductance of,

$$L_{P1,P2} = L_{AI} - \frac{1}{\omega^2 C_{S1,S2}} \quad (1)$$

where $L_{P1,P2}$ refers to L_{P1} or L_{P2}, and $C_{S1,S2}$ refers to C_{S1} or C_{S2} correspondingly. As previously mentioned, the three identical active inductors with a single control voltage are used to tune the centre frequency of the filter. The topology here differs from the work in [4], which had different active inductors with large series capacitors connected for their DC blocks and had a fixed operation frequency. The capacitors (C_M) at both sides of the filter in Fig. 1*a* belong to two L-section LC matching networks, as used to match the inner high characteristic impedance to 50 Ω for measurement. The shunt inductors in these matching networks have been combined into the two inductors (L_{P1}). More details on the theoretic design of a coupled-resonator filter can be found in [1].

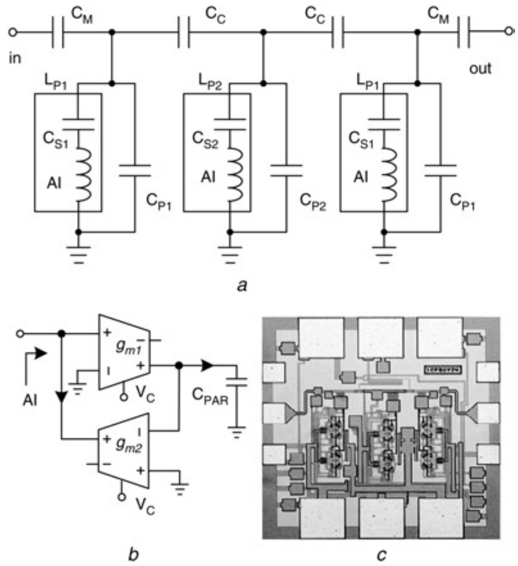

Fig. 1 *MMIC bandpass filter using active coupled resonators (Fig. 1a); tunable active inductor (AI) using two high-speed OTAs (Fig. 1b); microphotograph of fabricated bandpass filter (Fig. 1c)*

The identical tunable active inductor is presented in Fig. 1*b*. It is realised using two CMOS high-speed operational transconductance amplifiers (OTAs) developed in our previous work [7]. A feedforward-regulated cascode topology is employed in the OTAs, which has been demonstrated to have high-speed performance. As shown in Fig. 1*b*, a common active-inductor topology [8] is adopted to implement the active inductor, where two OTAs are connected end-to-end to compose an impedance inverter. The active inductance is achieved by impedance-inverting a capacitance C_{PAR} that is formed by the OTAs' input/output parasitic capacitance. The active inductance is given by

$$L = C_{PAR}/(g_{m1} \cdot g_{m2}) \quad (2)$$

where g_{m1} and g_{m2} are the transconductance of the two OTAs. Equation (2) suggests that the active inductance can be tuned by changing the two OTAs, transconductance. This is done through the OTAs' control voltage V_C, which is the mentioned single control voltage to tune the filter's centre frequency.

Experimental results: The active bandpass filter was designed and fabricated using 0.18 μm CMOS technology. A microphotograph of the fabricated filter is presented in Fig. 1*c*. The filter measures 520 × 540 μm^2 or 0.28 mm^2 including bonding pads, resulting in the smallest size of this type reported to date (see Table 1). The filter is supplied by ±1.5 V and consumes 41 mW of DC power.

The active inductor's control voltage V_C was designed to tune the filter's centre frequency. As shown in Fig. 2, a very wide tuning from 1.56 to 2.07 GHz (centre frequencies) was achieved in the measurement, resulting in a 0.51 GHz, or 28% tuning range. The insertion loss at the centre frequency varies from a minimum of -3.5 dB to a maximum of -6.6 dB over the tuning range. Furthermore, the frequency response of the filter is highly symmetric about the centre frequencies and the roll-off beyond the passband is very steep. Fig. 3 presents the centre frequency against frequency tuning voltage V_C, and Fig. 4 gives the input reflection coefficient and its transmission. The variation on the small matching capacitors (C_M = 0.33 pF) in the fabrication is considered for the modest input reflection coefficient.

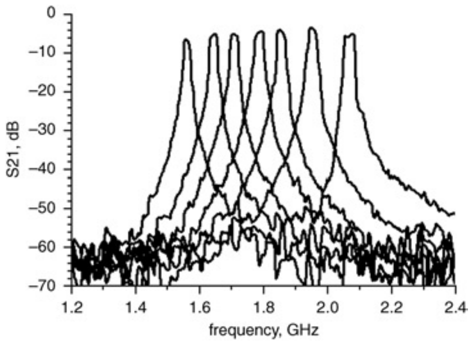

Fig. 2 *Measured transmission in different control voltages*

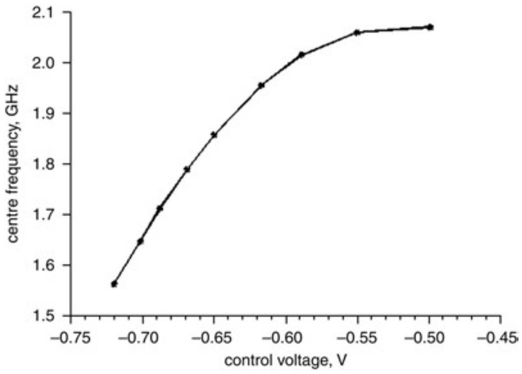

Fig. 3 *Measured centre frequency against frequency tuning voltage V_C*

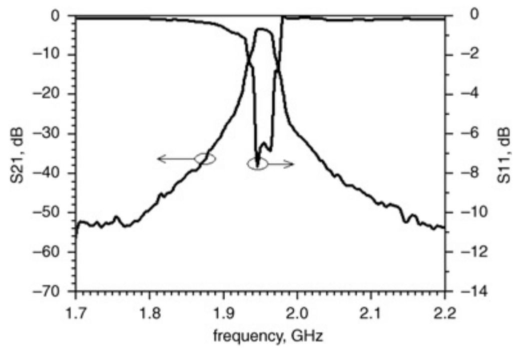

Fig. 4 *Measured input reflection coefficient and its transmission at $V_C = -0.617$ V*

A performance summary of this filter and the previous active filters also using coupled resonators are shown in Table 1 for comparison. The filter in this Letter is the smallest of all by a factor of at least 5, and it has the second largest tuning range. The power consumption of this filter (41 mW) compares very favourably with the other active filters in Table 1. Furthermore, this filter is the first of its type in a digital CMOS technology.

Conclusion: A very wide tuning range MMIC active bandpass filter has been experimentally demonstrated, which outperforms the previous active filters regarding its tuning range, size and DC power consumption together. The designed filter is very suitable for applications in multi-band systems.

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